Fiber lasers and amplifiers for Earth/planetary science & exploration

at NASA Goddard Space Flight Center

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NASA Goddard Space Flight Center
Greenbelt, MD 20771

NASA Earth Science Technology Conference
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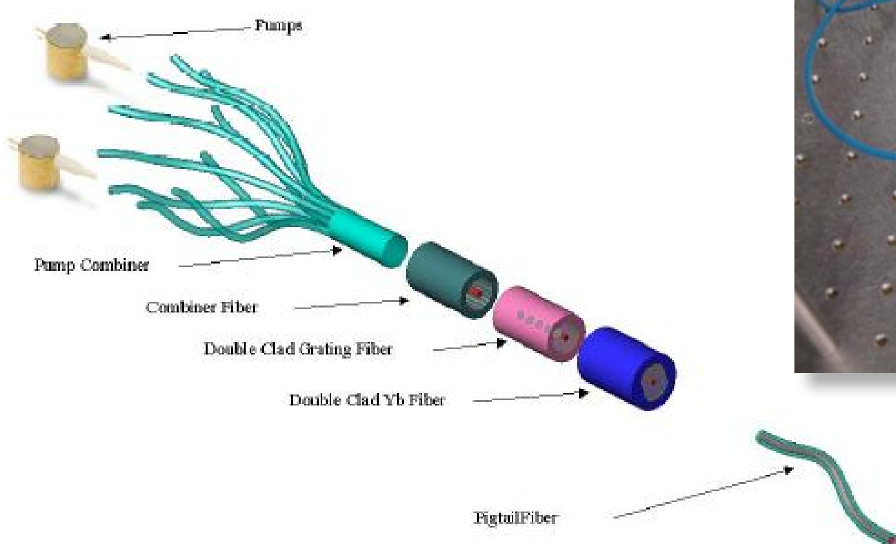
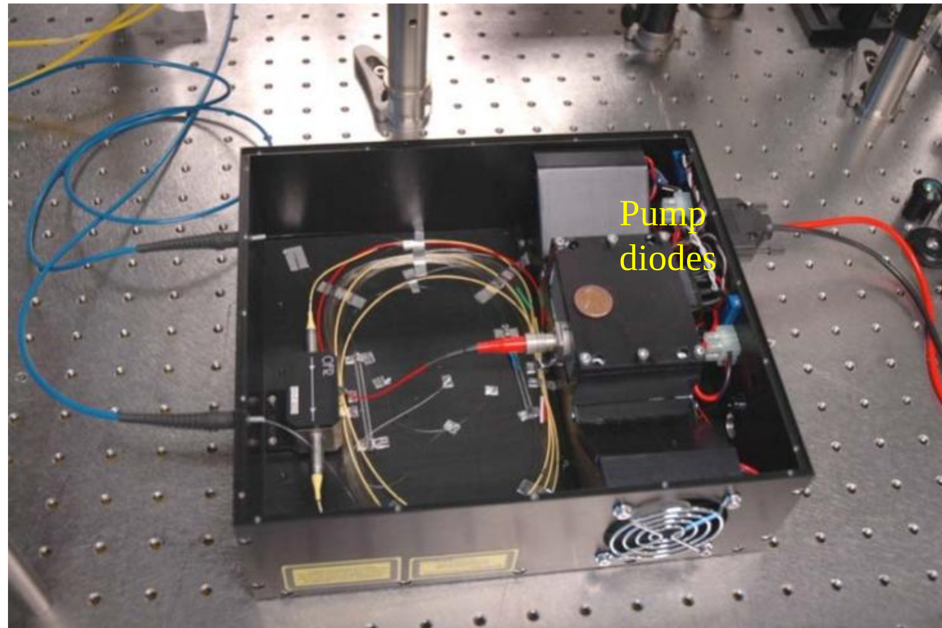
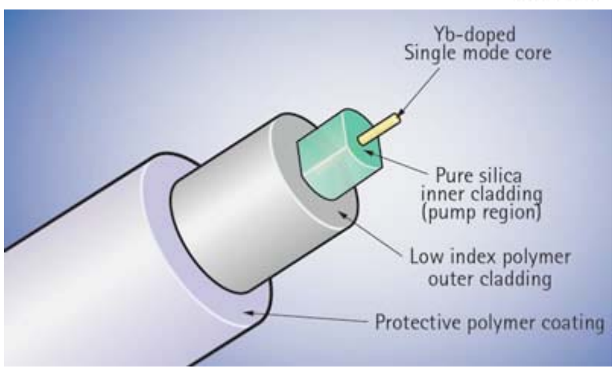
Fiber lasers

Fiber laser diagram

(Cross sections shown for display purposes. The fiber laser has a monolithic structure.)







Key features:

- Closed cavity - no contamination
- Fiber architecture - no misalignment
- Diode pumping technology is more reliable
- Distributed thermal load
- High electrical efficiency
- Leverages Billions of $ of investment from industry
- Components built to Telcordia standards (can be even more stringent than space flight)
- Availability of parts
- Wavelength flexibility

Fiber lasers
State-of-the-art January 2006

Conference 6102: Fiber Lasers III: Technology, Systems, and Applications

Monday-Thursday 23-26 January 2006
Proceedings of SPIE Vol. 6102

6102-04, Session 2
Kilowatt fiber lasers and beyond

D. N. Payne, Univ. of Southampton (United Kingdom)

Born out of the telecom revolution, the supreme attributes of rare-earth doped fibers has allowed Yb-doped fiber lasers to be power-scaled from 0.1 to several kW's in only a few years. Remarkably, we still see fiber lasers being limited by the diodes rather than the fibers themselves, even as output powers have continued to rise well into the multi-kW regime. Despite these impressive results, high-power fiber laser development is still in its infancy with a high rate of progress. Limited investment rather than the fundamentals of the technology is the biggest hurdle to the 10 kW-level from a single-emitter diffraction-limited fiber source. Looking to the future, fiber sources are also extremely attractive for beam combining for power-scaling to perhaps 100's of kW. Of particular interest here is the astounding single-frequency powers that have been obtained, also now approaching 1 kW.

Numerous fiber laser pulse schemes are also available, giving pulses from the femtosecond to the microsecond regime with peak power (compressed) in the multi MW's . With large core designs, pulse energies up to 0.1 J can be obtained. Wavelengths from 800 nm to 2100 nm and beyond are seamlessly available through appropriate choice of rare-earth dopant or through Raman shifting. Moreover, these characteristics can be realized with exceptional control of the output stability and beam profile. The key to this is the ability of fibers to combine high power and high efficiency with high broadband gain and excellent beam quality in sophisticated master oscillator - power amplifier configurations.

This presentation will discuss progress and prospects for high-power fiber sources, treating "simple" power-scaling as well as more sophisticated single-frequency and pulsed sources at different wavelengths. Adding the attributes of small size, maintenance-free operation, and high thermal and electrical efficiency, we see that fiber lasers have the potential to change every industry and discipline they encounter and challenge currently held views on how to make things, how to repair things, and how to destroy things.

6102-21, Session 7
MW peak-power, mJ pulse energy, multi-kHz repetition rate pulses from Yb-doped fiber amplifiers

F. Di Teodoro, C. Brooks, Aculight Corp.

Despite the impressive progress in power scaling CW and quasi-CW optical fiber sources, fewer high-power results are available in the "Q-switch" pulsed regime characterized by pulse durations of a few ns or less and multi-kHz pulse repetition rates. A challenge for fiber amplifiers operating in this regime is the generation of high peak power with minimal nonlinear effects. Additional challenges include containment of inter-pulse amplified spontaneous emission and avoidance of optical damages. In this paper, we demonstrate the potential of fibers to generate high peak powers in pulses of excellent spectral/spatial quality.

In the first setup, a 1-ns pulse, Q-switched microchip laser (1062nm) operating at ~10-kHz pulse repetition rate (PRR) seeded a dual-stage amplifier featuring a 40-µm-core Yb-doped photonic-crystal fiber (PCF) as the power amplifier. From this amplifier, we obtained diffraction-limited (M2 = 1.05), ~1ns pulses of 1.1mJ energy, ~1.1MW peak power, ~10.2W average-power, spectral linewidth ~9GHz, negligible nonlinearities, and slope efficiency >73%. To our knowledge, these values amount to the best combined performance from a multi-kHz fiber source.

In the second setup, we replaced the seed source with a shorter-pulse (<500ps) microchip laser (1064nm) of PRR ~ 13.4 kHz and obtained diffraction-limited (M2=1.05), ~450ps pulses of energy \>0.7mJ, peak power in excess of 1.5 MW (the highest from a diffraction-limited fiber source), average power ~9.5W, spectral linewidth <35 GHz. To show further power scaling, these pulses were amplified in a 140-µm-core Yb-doped fiber, which yielded multimode (M2 ~ 9), 2.2mJ-energy, 30-W average-power pulses of peak power in excess of 4.5MW, the highest ever obtained in an optical fiber source.

6102-25, Session 8
10 mJ pulse energy and 200 W average power Yb-doped fiber laser

S. Maryashin, A. O. Unt, V. P. Gapontsev, IPG Laser GmbH (Germany)

We report on the 10 mJ energy per pulse and 200 W average power pulsed Yb fiber laser. MOPFA configuration with 65 um core multi-clad powerful amplifier allows to provide 300 ns optical pulses in wide frequency range of 1 - 50 kHz. Master oscillator is based on first relaxation peak all-fiber generator. Wall plug efficiency of 25% and 10 m long delivery output with isolated head are essential features for industrial product. More details and results would be discussed.

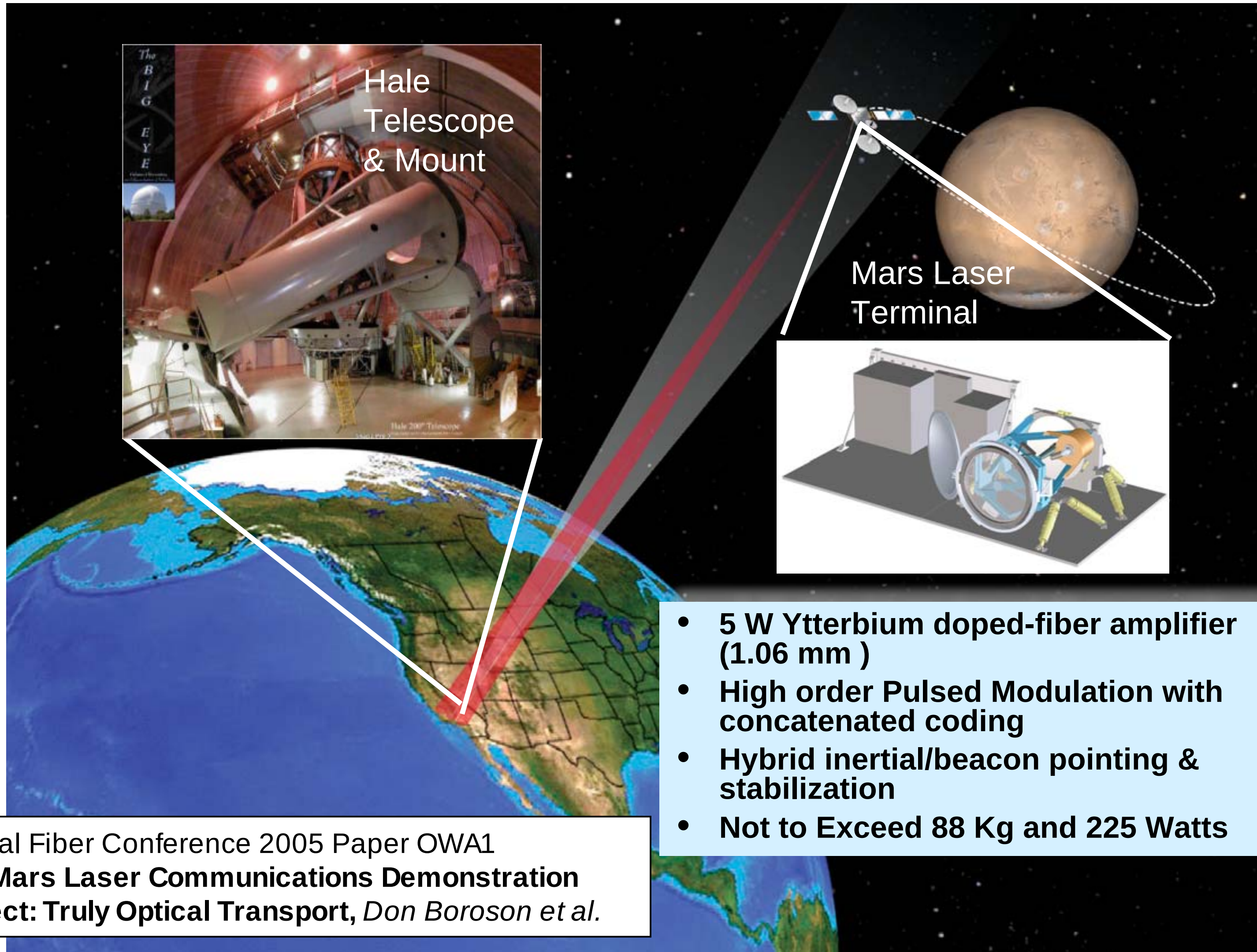
6102-61, Session 17
300W single-frequency, single-mode, all-fiber format ytterbium amplifier operating at 1060-1070-nm wavelength range

O. Shkurikhin, N. S. Platonov, D. V. Gapontsev, R. Yagodkin, IPG Photonics Corp.; V. P. Gapontsev, IPG Laser GmbH (Germany)

300W single frequency ytterbium amplifier with M2<1.3 is demonstrated in all-fiber format for 1060-1070 nm wavelength band. Using an optimized splicing conditions and specially designed Yb-doped fiber at the booster stage, the amplifier provides single frequency amplification without any nonlinear effects including SBS. No output power saturation was observed and output optical power was only limited by pump power. We also did not observed any noticeable noises and roll off of output power due to high order modes excitation or other nonlinear phenomena. More resend results would be presented and discussed.

Free-Space Laser Communications

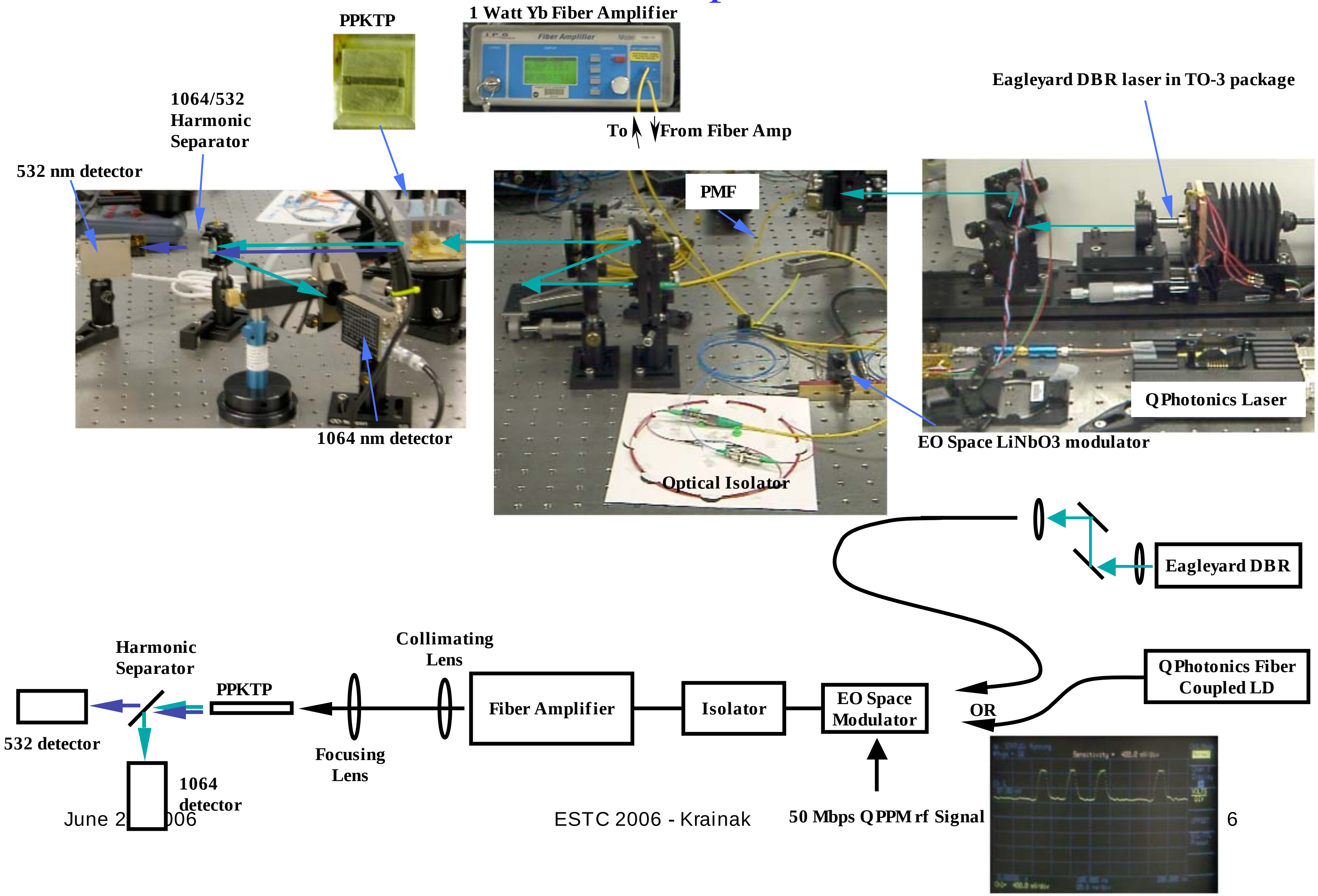
Satellite Optical Communications
Mars Laser Communication Demonstration



- **5 W Ytterbium doped-fiber amplifier (1.06 mm)**
- **High order Pulsed Modulation with concatenated coding**
- **Hybrid inertial/beacon pointing & stabilization**
- **Not to Exceed 88 Kg and 225 Watts**

Optical Fiber Conference 2005 Paper OWA1
The Mars Laser Communications Demonstration Project: Truly Optical Transport, *Don Boroson et al.*

Free-Space Laser Communications
50 Mbps Quaternary Pulse Position Modulation (Q-PPM) Link Experiment

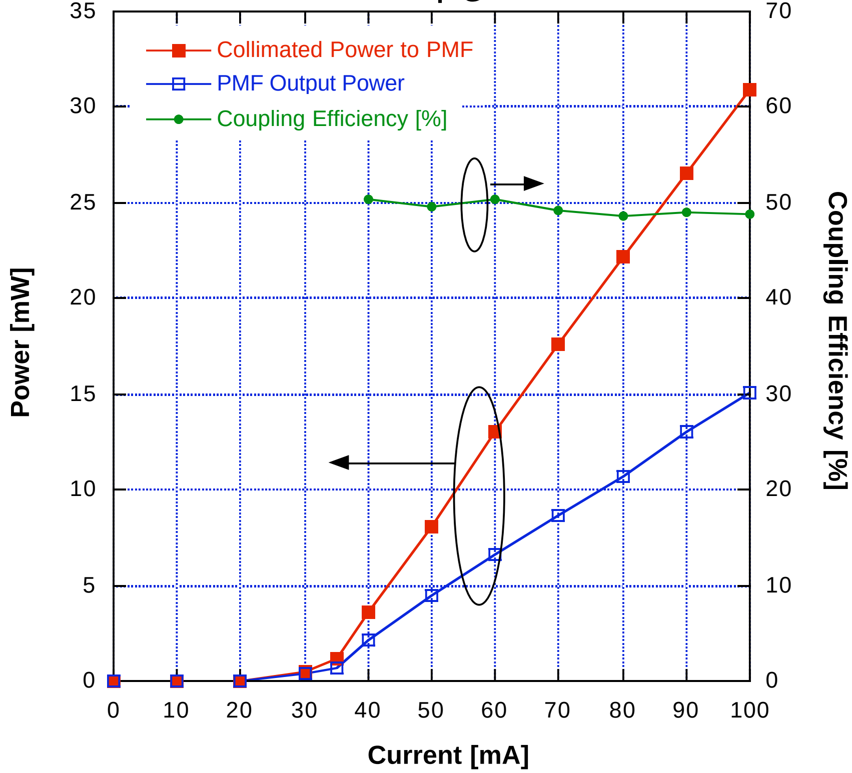


Free-Space Laser Communications

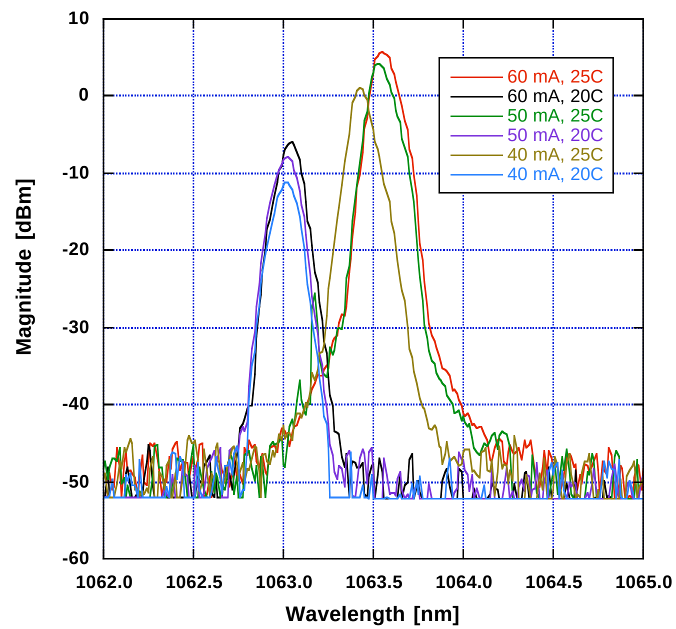
Ytterbium fiber MOPA laser transmitter
50 Mbps data at 1064 nm and 532 nm

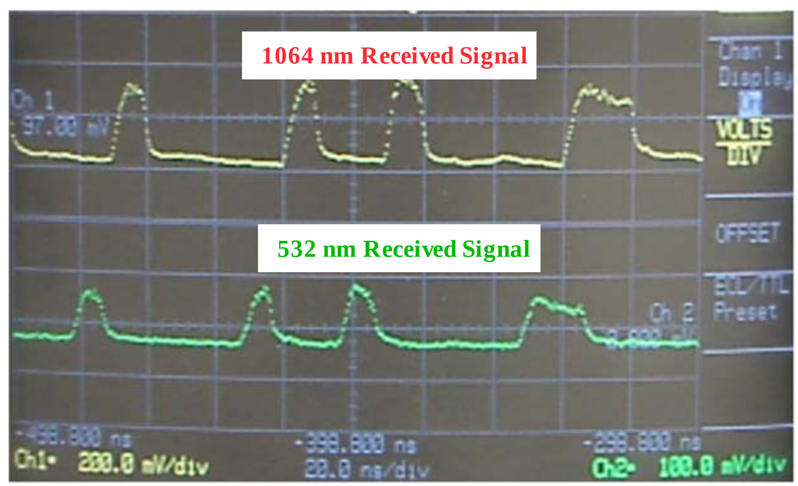
Goddard Space Flight Center

LI Curve of Eagleyard DBR coupled into PMF Case Temp @ 25C



Eagleyard DBR Spectral Data





Data taken with Yb fiber amplifier at 1 W average power output, seeded with DBR laser at 60 mA (20C) or optical power of 7 mW.

Fiber laser

NASA leverage for exploration and science

Goddard
Space
Flight Center

Optical Fiber Conference 2006

PDP17

High Reliability 49 dB Gain, 13W PM Fiber Amplifier at 1550 nm with 30 dB PER and Record Efficiency

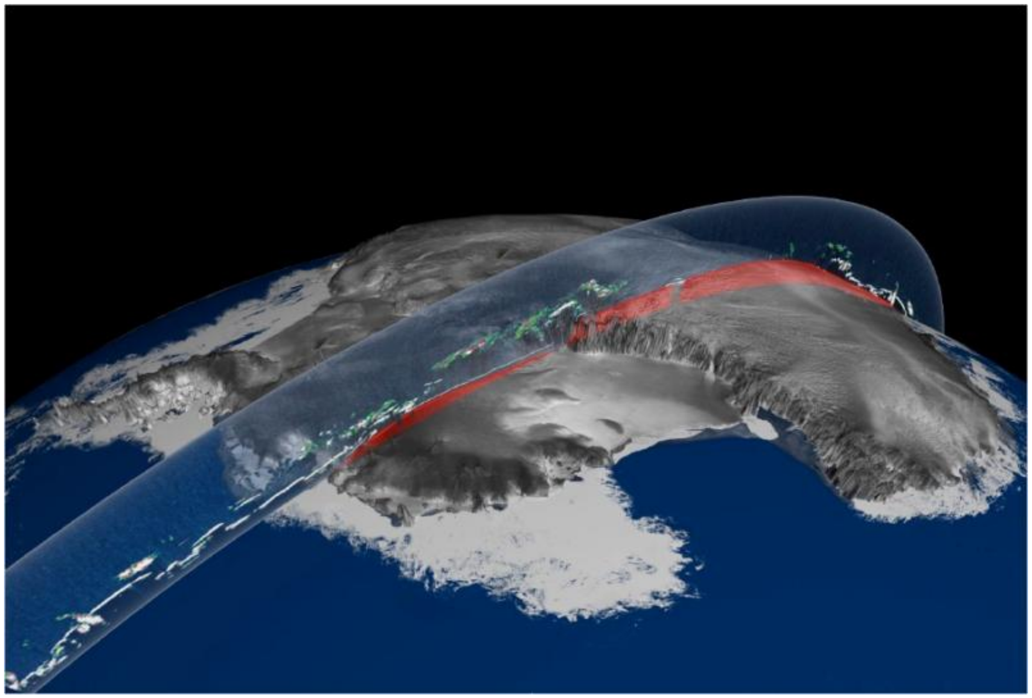
P. Wysocki, T. Wood, A. Grant, D. Holcomb, K. Chang, M. Santo, L. Braun, G. Johnson
Lucent Technologies, Bell Laboratories ,600 Mountain Avenue, Murray Hill, NJ 07974

Abstract: We present a single-mode, polarization-maintaining, Er/Yb-codoped cladding-pumped amplifier with up to 49 dB of gain, 13W output power, a 30 dB polarization-extinction ratio, 12.9% electrical to optical conversion efficiency, and 42% optical-optical power-stage fiber slope efficiency. This is the most efficient highest PER HPOA ever reported near 1550 nm. The HPOA was built using all fiber-based components qualifiable for long missions in harsh environments.

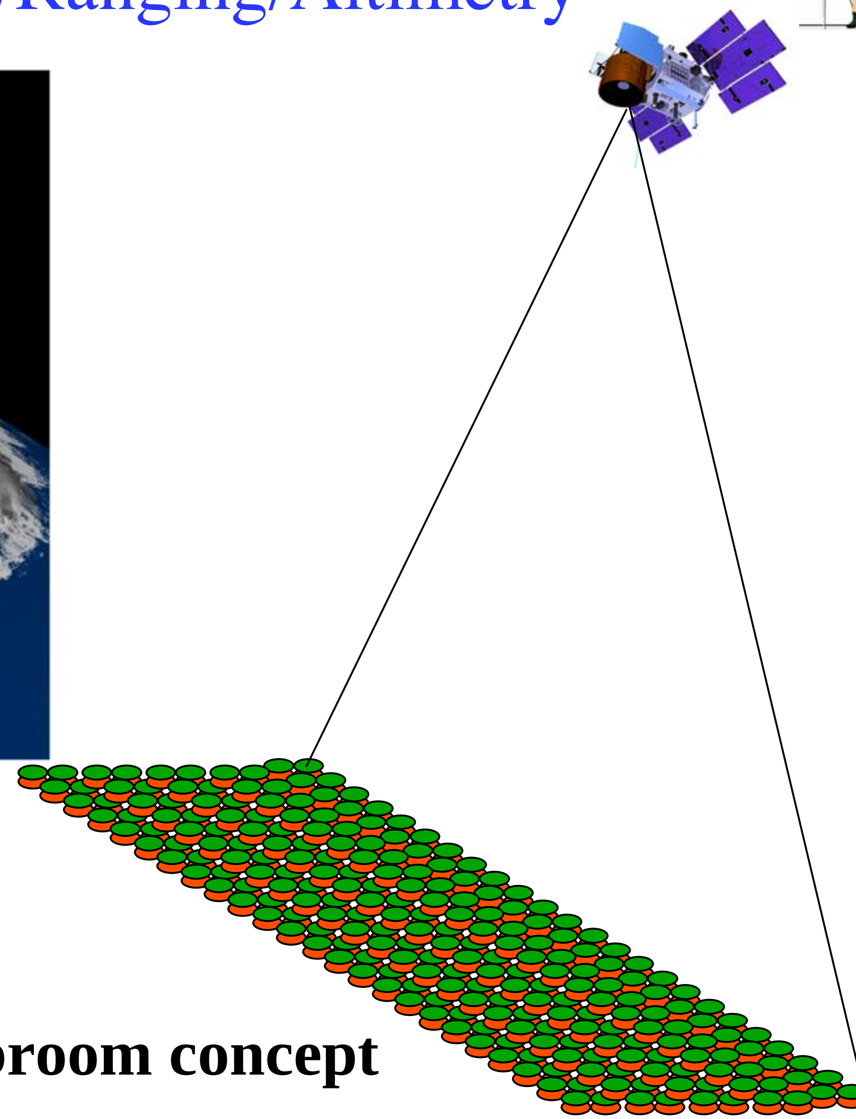
OCIS codes: 060.2320, 060.2420, 140.4480

Laser Ranging/Mapping

Planetary
Laser Mapping/Ranging/Altimetry

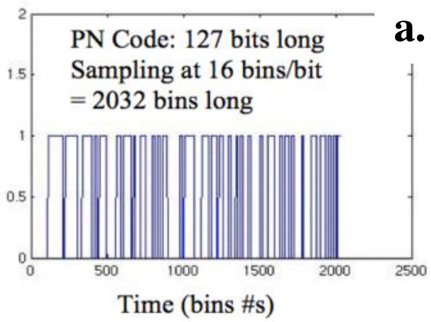


ICESat single track

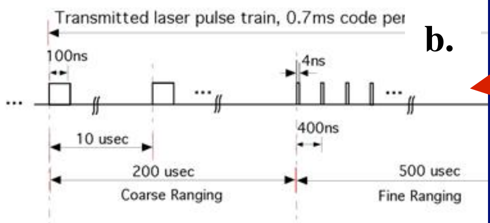


Pushbroom concept

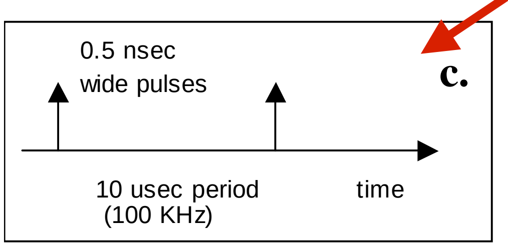
Swath Mapping Laser Altimeter Measurement Technique Options



a.



b.



c.

Swath Mapping Altimeter Measurement Options

Modulation & wavelength	Typical Laser Duty Cycle & Pk Power	Receiver Measurement Technique: Analog	Multi-photon	Single Photon
Pn Code	50%			
532 nm	Watts	N	N	Yb fiber, SPCM
770 nm		N	N	Er fiber, SPCM
1064 nm		N	N	**Yb fiber, IPD***
Low Duty Cycle	1%			
532 nm	~20W	N	Yb fiber, MCP-PMT	Yb fiber, SPCM
770 nm		N	Er fiber, MCP-PMT	Er fiber, SPCM
1064 nm		N	Yb fiber, IPD	Yb fiber, IPD
MicroPulse	0.01%			
532 nm	KW	Uchip, Si APD	Uchip, MCP-PMT	**Uchip, SPCM***
		Yb fiber, Si APD	Yb fiber, MCP-PMT	Yb fiber, SPCM
770 nm		N	Er Fiber, IPD	Er fiber, SPCM
1064 nm		Uchip, Si APD	Uchip, IPD	**Uchip, IPD***
		Yb fiber, Si APD	Yb fiber, IPD	Yb fiber, IPD

* - initial work

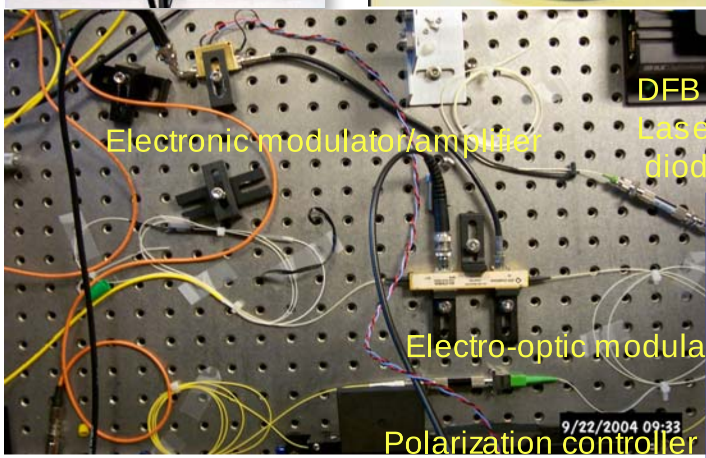
Summary:

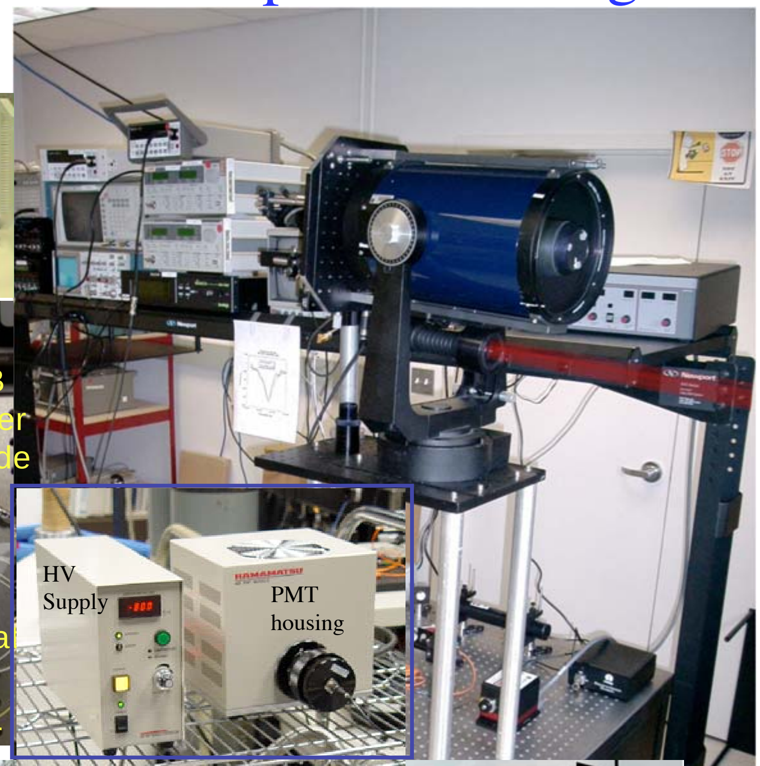
Concentrate work in lower RH region

1570 nm PN code measurement demonstration
Breadboard & Optical test range

PN Code Generator

EDFA (1570 nm)

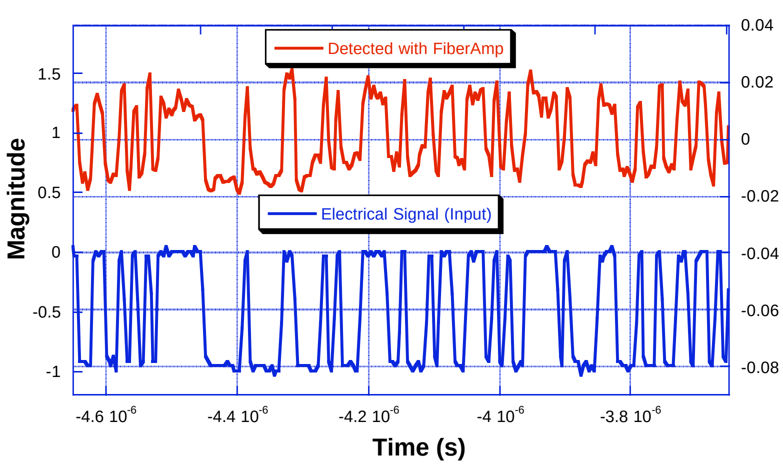




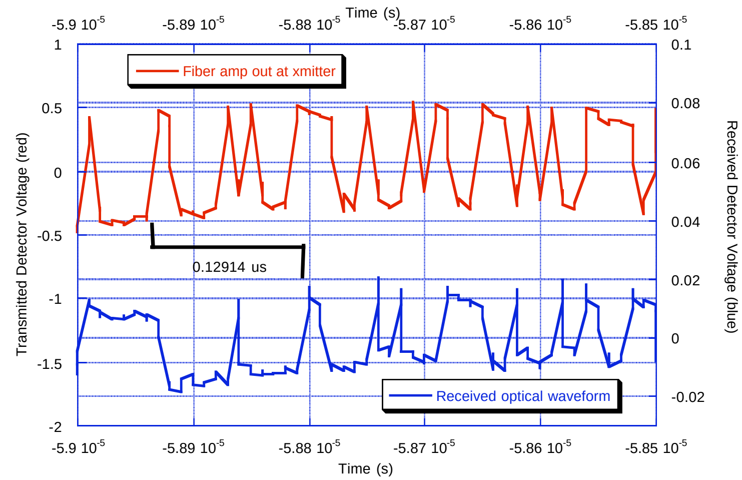
Tree trunk

Demo Experiments - 1570 nm,
100 MHz PN Code modulation & Flat (impulse) target

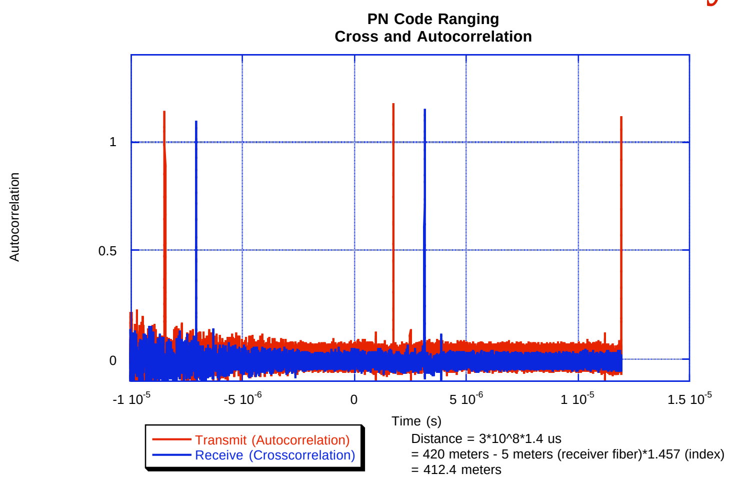
Electrical drive signal (PN Code)
& fiber amplifier (laser) output

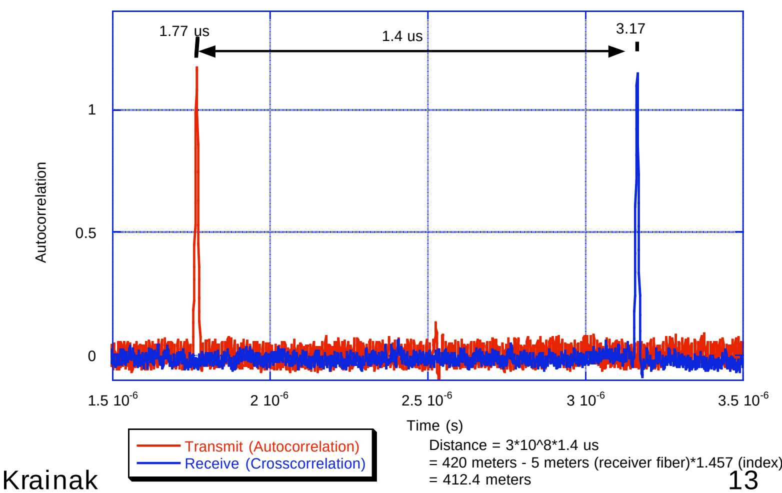


Detail of transmitted & echo code segments



Cross- Correlations yield round trip range delay of 412.4 m

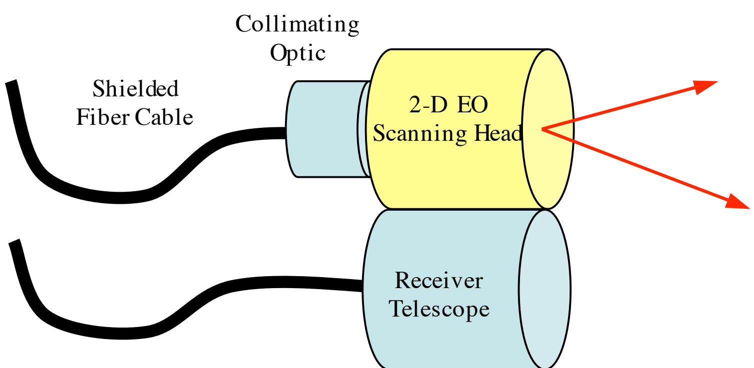




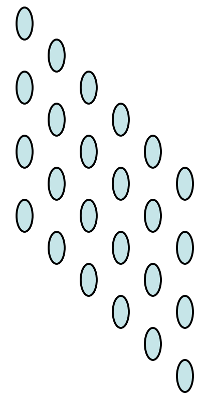
Specifications of Prototype Pulsed Ytterbium Fiber Laser for Swath Mapping Altimeter

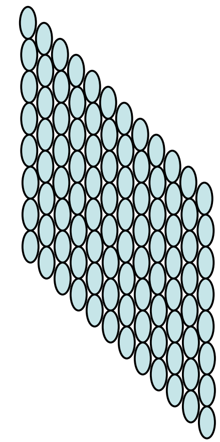
Center Wavelength	Single Wavelength between 1040-1070 nm (No tunability is required)
Output Spectral bandwidth	< 200pm while operating at 10 kW peak with 0.7 ns pulse width at 100 kHz rep rate
Maximum output port out of band power density	-20 dBc maximum value over 900-1200 nm out of band power excludes 1 nm carrier bandwidth
Output pulse width	0.7 – 1.5ns FWHM (any pulse width in this range is acceptable)
Pulse repetition rate	0.1 MHz – 2 MHz in 10 kHz increments (user selectable)
Pulse on/off ratio	The output pulse on/off ratio in time should be better than 1000
Output beam quality	M^2<1.4
Optical output power	10W average power at 1 MHz repetition rate with 1 ns pulse width
Peak output optical power	1 kW – 10 kW adjustable (at a rep. rate of 1 MHz and pulse width of 1 ns)
Output power stability	< 5% variation in average power over one hour of operation (Testing conditions: 10 watts at a rep. rate of 1 MHz and pulse width of 1 ns)

Electro-Optic 2-D Scanning Imaging Lidar for Pose Sensing, Robotic Docking, and Hazard Avoidance

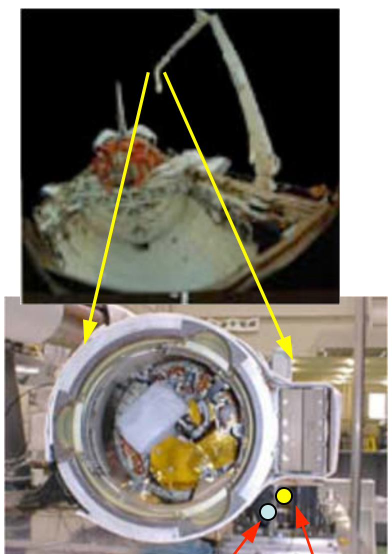


Sparse Footprints:
N# shots per pixel for
long range target acquisition…





Contiguous footprint pattern for optimum coverage and refresh rate…



Scanning laser Output window

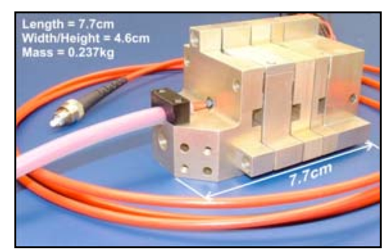
Receiver Telescope

EO Scanning output is capable of variable point cloud image production in real time: pixel density and refresh rate.

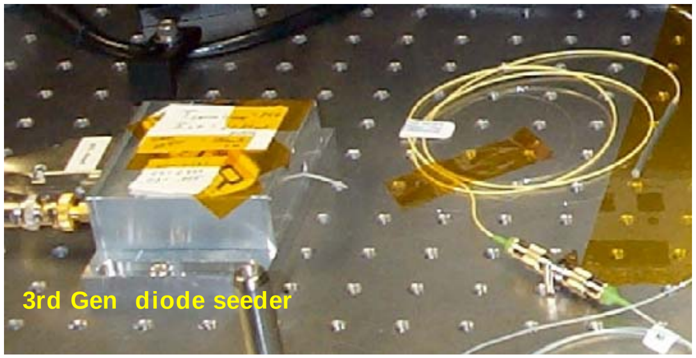
No moving parts and all-solid state deisgn means long lifetime, low mass, high effic.

Allows scalable field of view, and can switch to direct ranging mode down to 0 cm range (contact).

Variable Output Laser Transmitter (VOLT) is based on new flight qualified seed laser, developed under DDF and ESTO. Seeds diode pumped Yb:fiber amp for long range imaging and ranging.

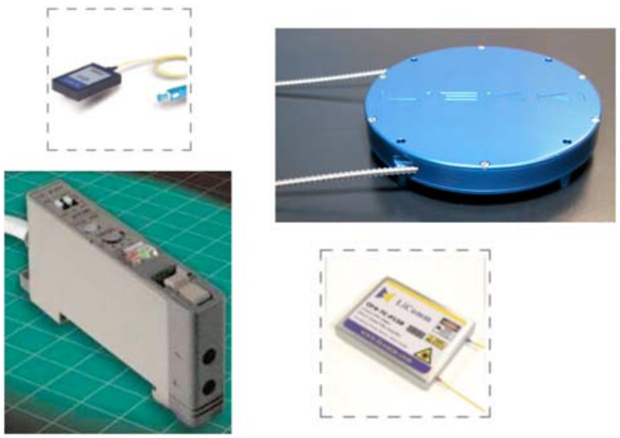


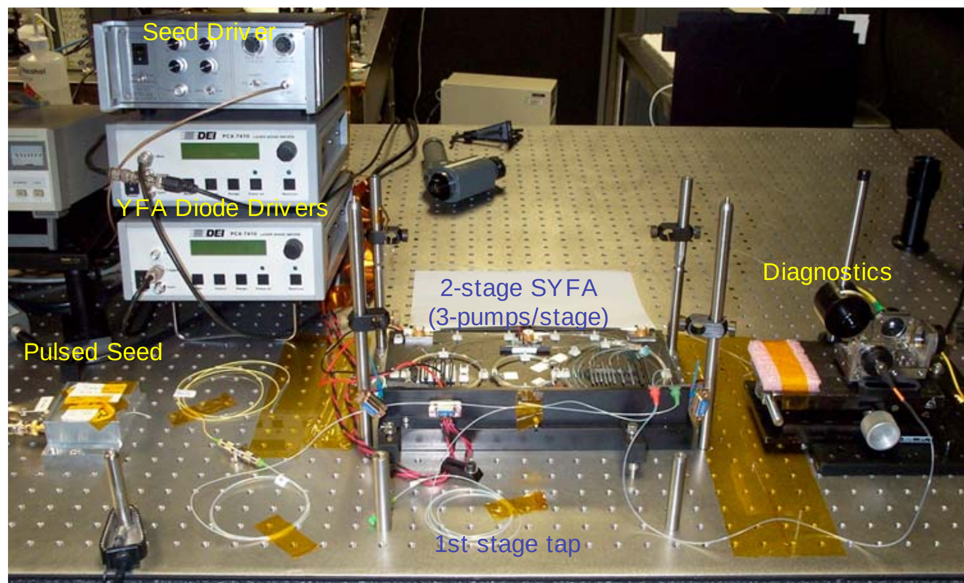
Laser Imaging System Packaging



All the components have been demonstrated in the lab. Now we have to begin the process of optimization and integration such that a complete, discrete scanning system if shown viable for further development for out-of-lab demonstrations.

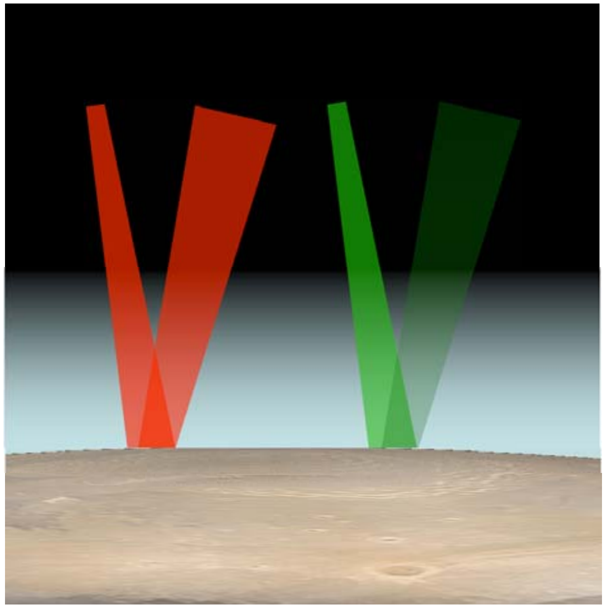
Fiber amp package potential:
current state of the art examples



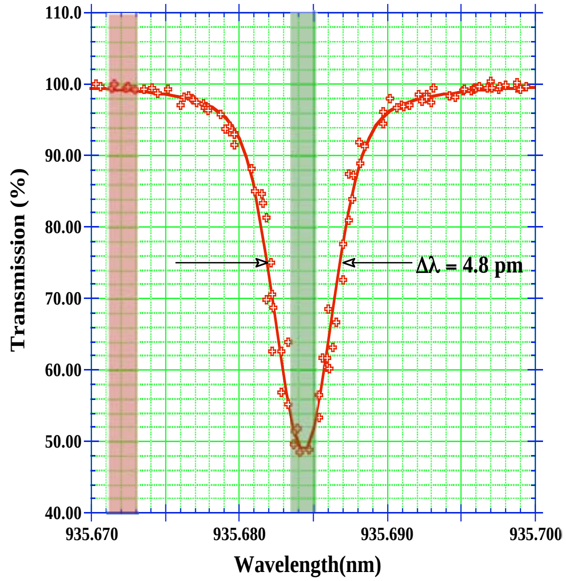


Atmospheric Gas Detection/Mapping
WATER VAPOR

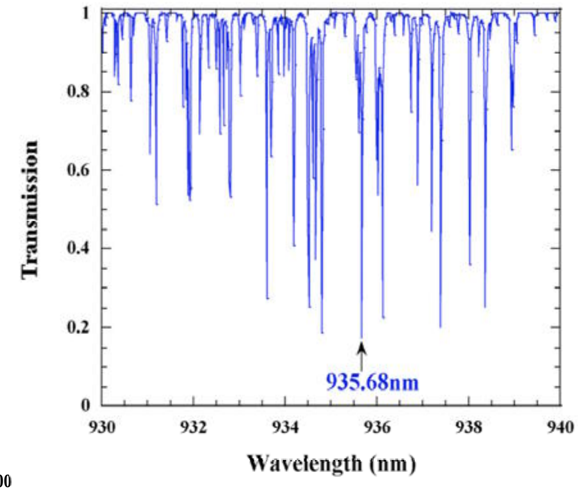
Laser Sounder Concept - Differential Absorption



Water Vapor Absorption @ 935.68 nm, 17 Torr (Saturated from Vacuum), ~23C˚ and in a 0.4m Optical Path using DBR A#7.

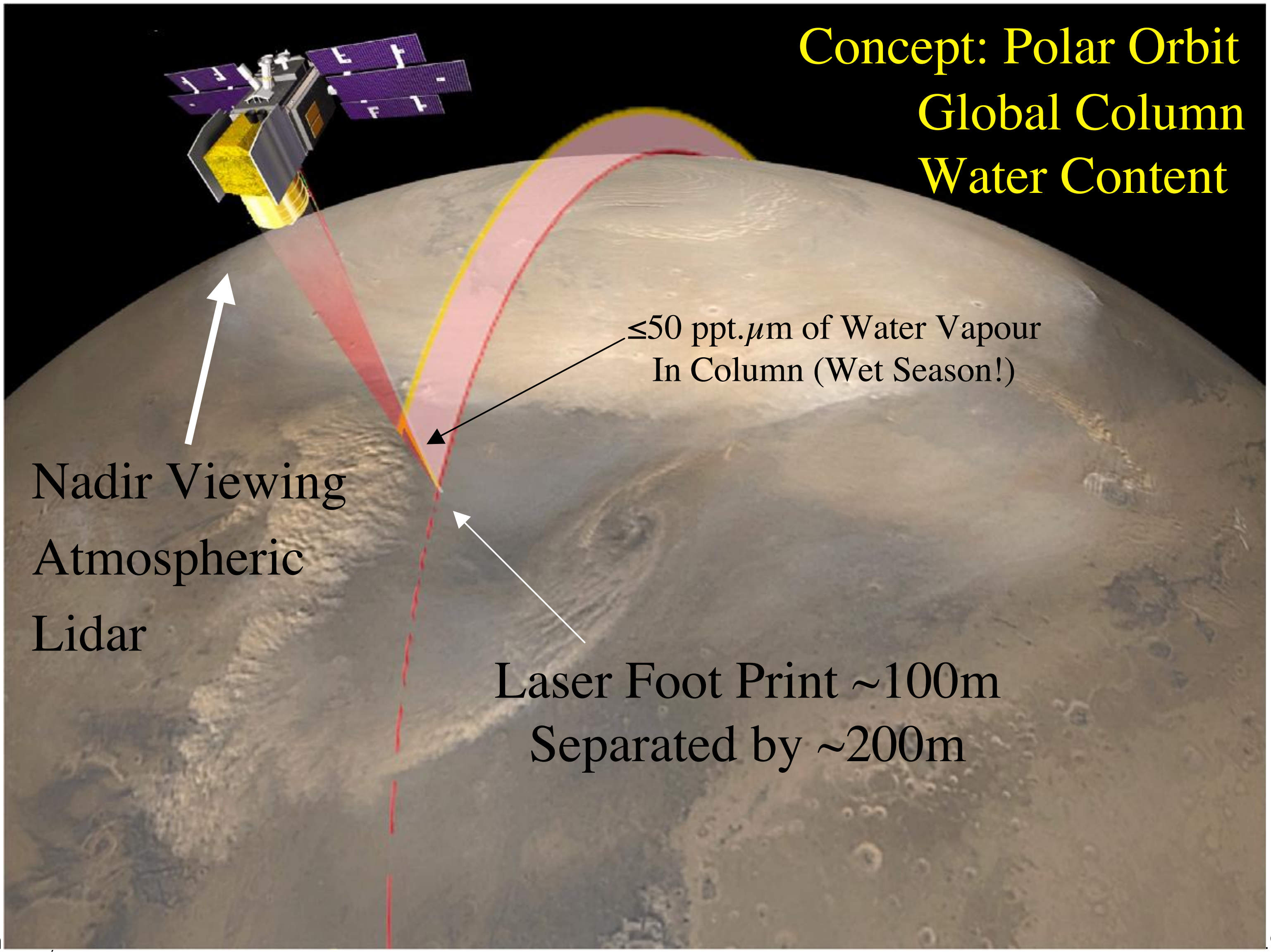


Transmission through 0.4m of pure water vapor at 935.68 nm, at ~12 mBarr and ~23C˚. The solid line is a numerical fit to the absorption profile.



--Sounder based concept--total water vapor column content
--Temporal resolution --Pulsed source --Back scatter cloud and aerosols

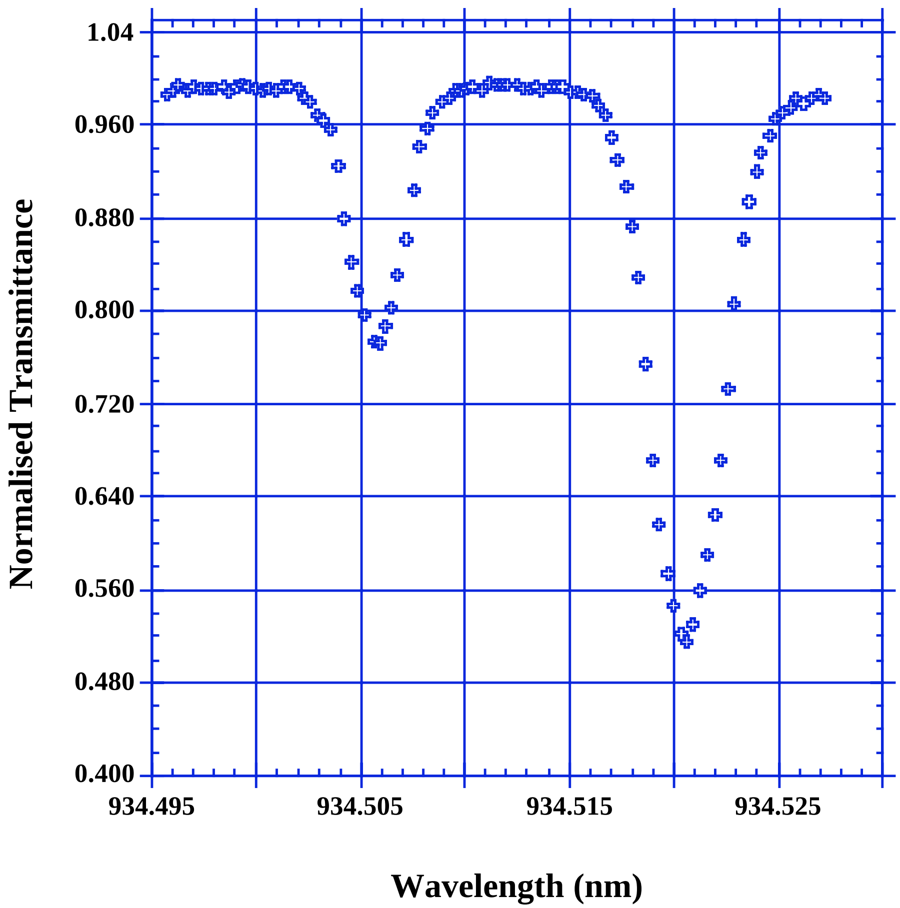
Mars Laser Sounder for Global Measurements of Water Vapor from Orbit



Water vapor measurement

for the 934.506 & 934.521 ($10700.6\ cm^{-1}$) H_2O Absorption.

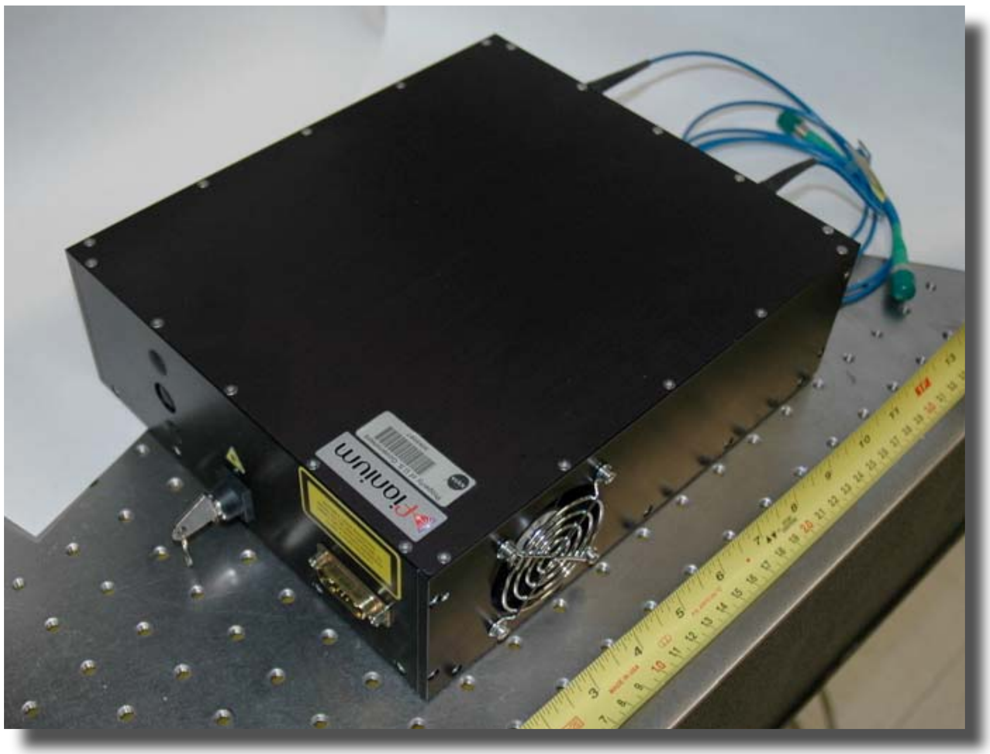
5mbar ~23C 10m



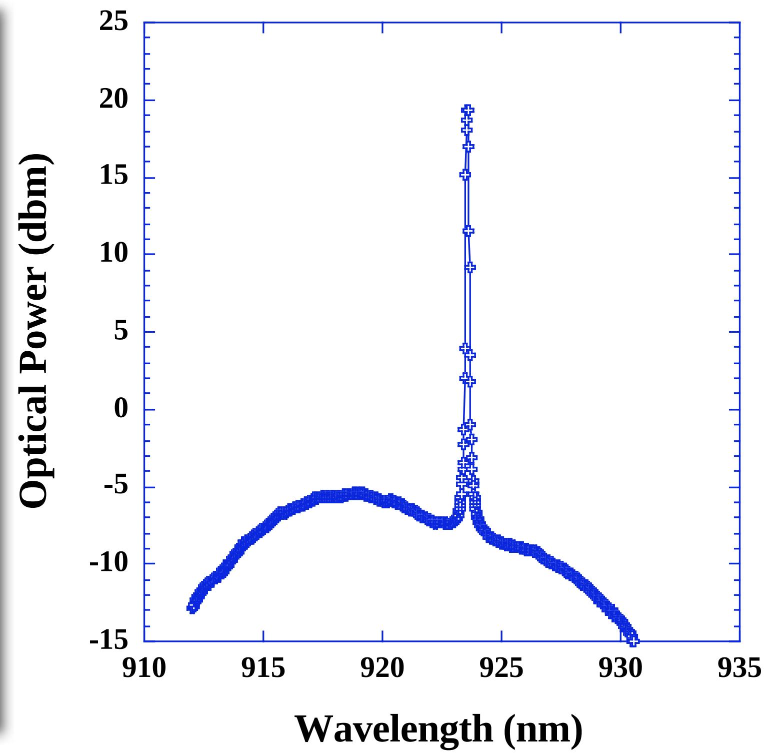
Wide tuning and Low Pressure ~Wavelength Calibration

Nd fiber amplifier (930 nm)
(for Mars-orbital Water Vapor Laser Sounder & NOAA ground based water vapor lidar)

0.5 W Nd-doped Optical Fiber Amplifier

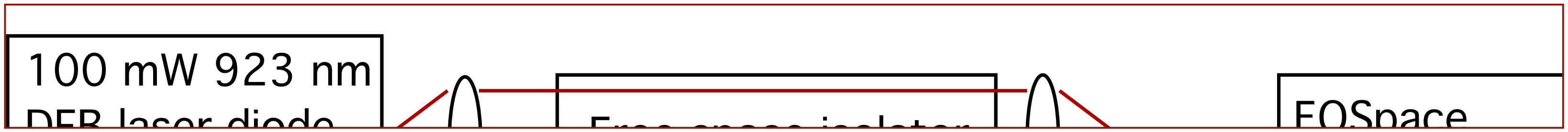


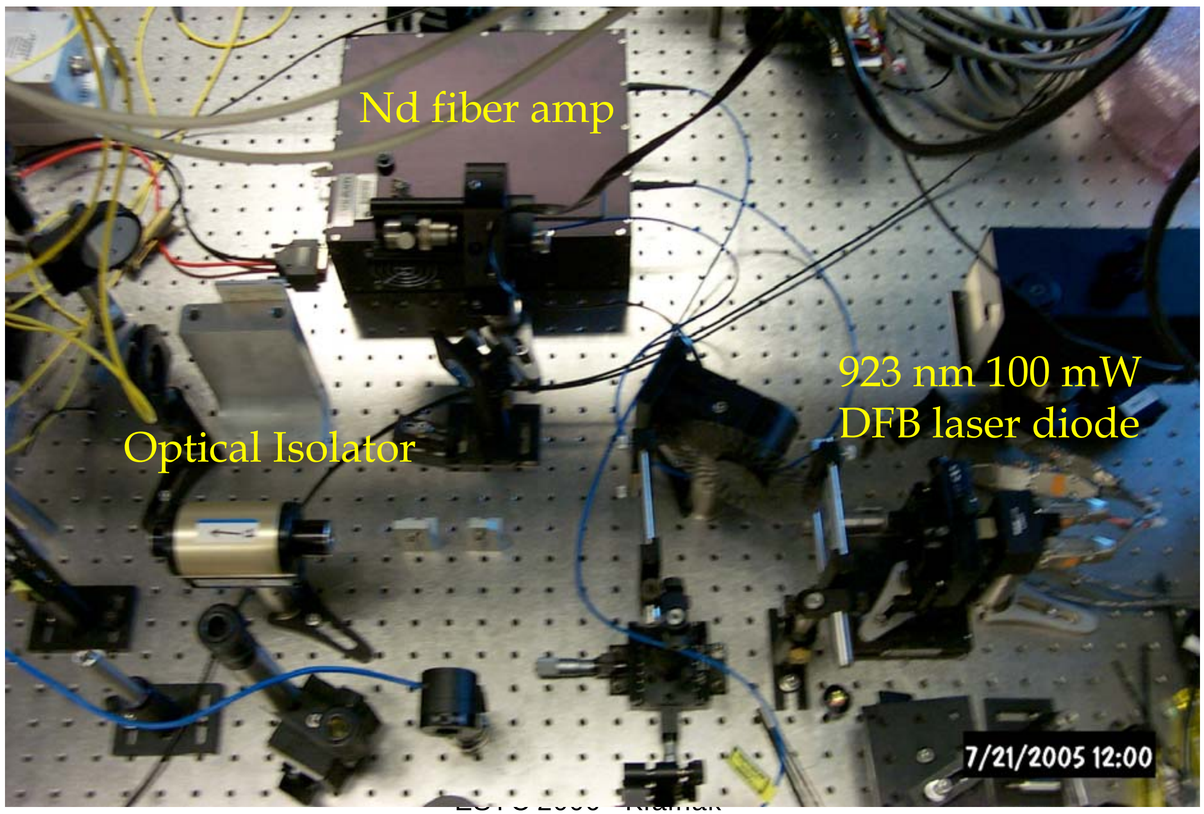
Output spectrum at ~17dB gain, output power ~100 mW



Expected ~25 db gain between 915 & 930 nm
15 Volt 10 amp power supply
Include up to 5 amps for onboard TEC coolers

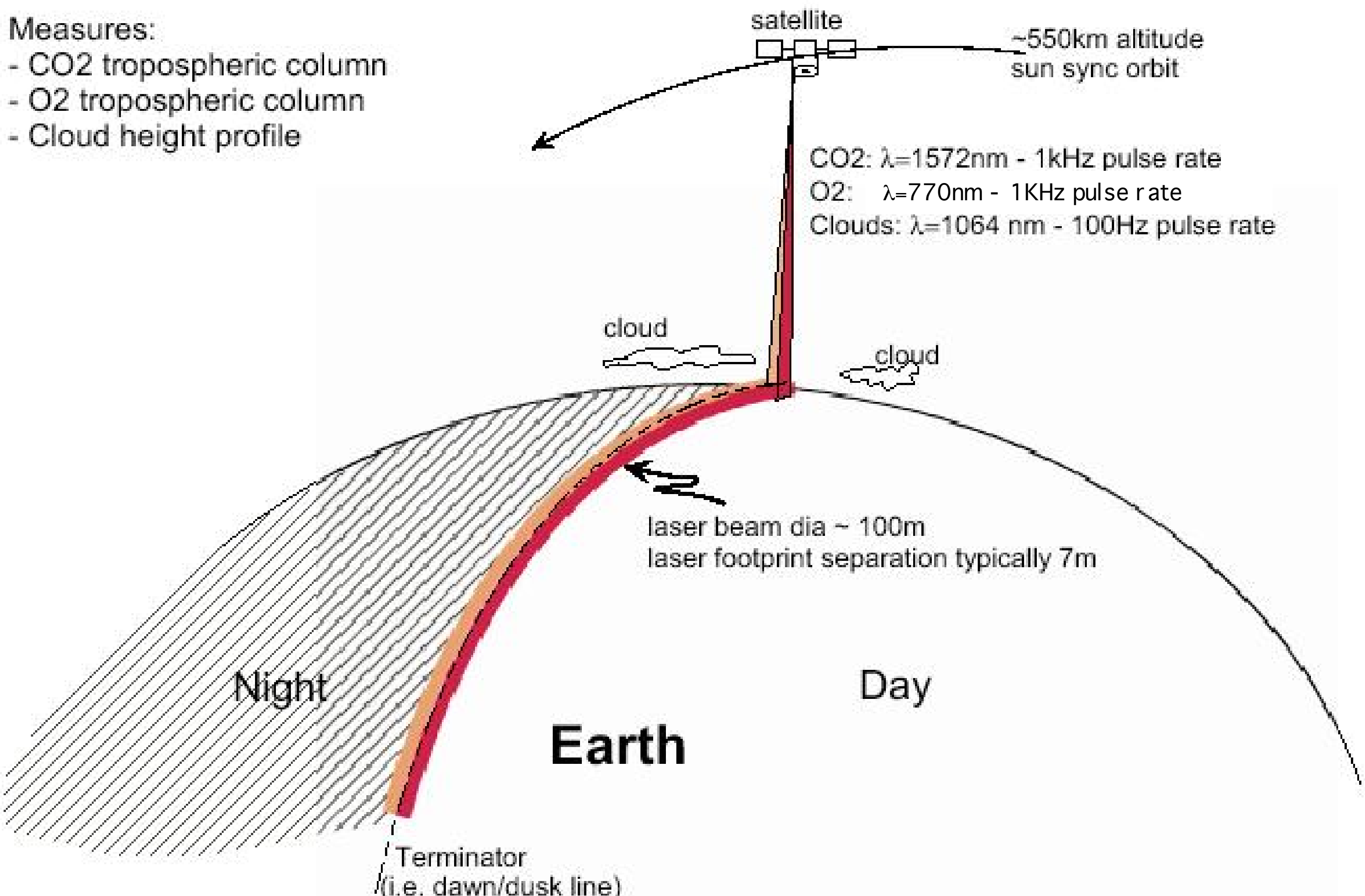
Nd fiber amplifier (923 nm) MOPA





Atmospheric Gas Detection/Mapping
CARBON DIOXIDE

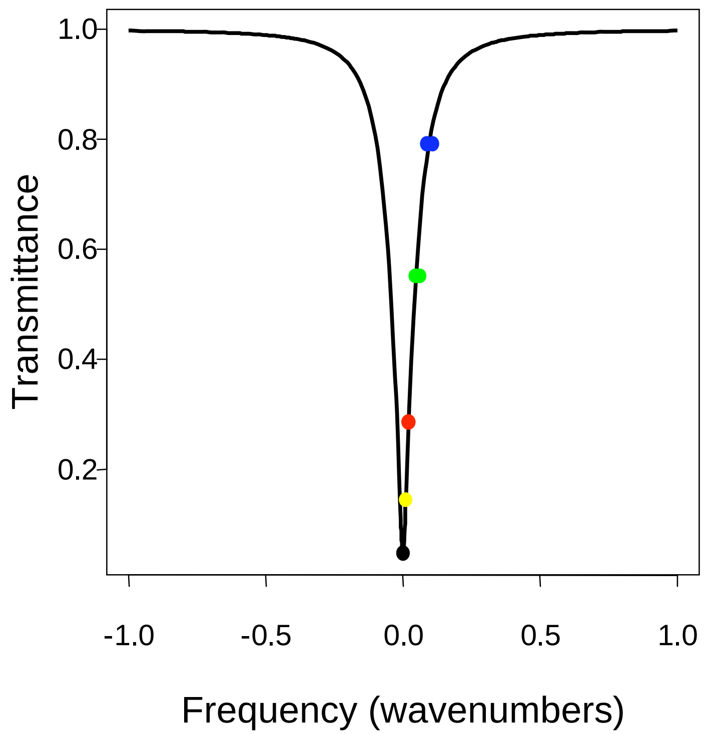
Laser Sounder for Remotely Measuring Atmospheric CO_2 et al. Concentrations [Earth and Mars]

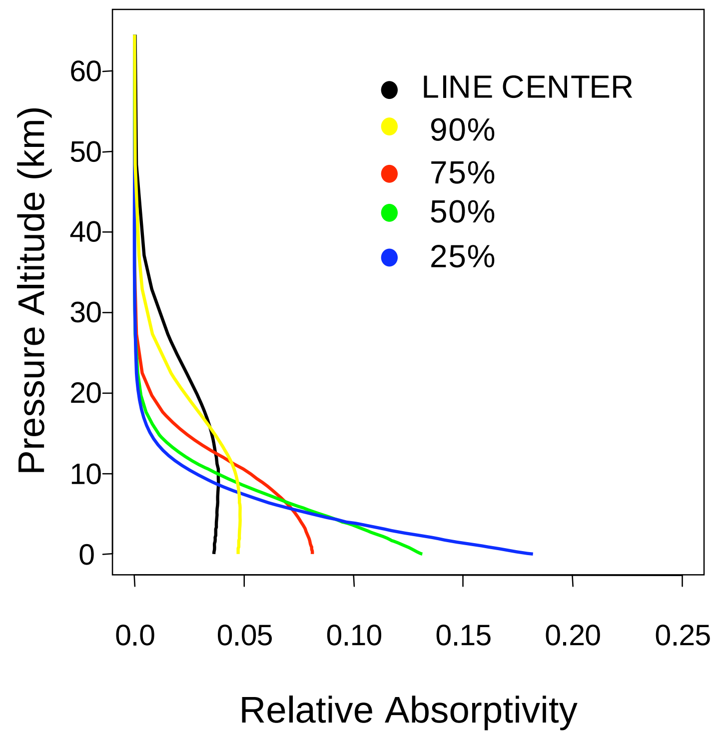


Laser Sounder
CO_2 vertical profiling via pressure broadening

Vertical sensitivity as a function of frequency for a line near 1.6 μm:

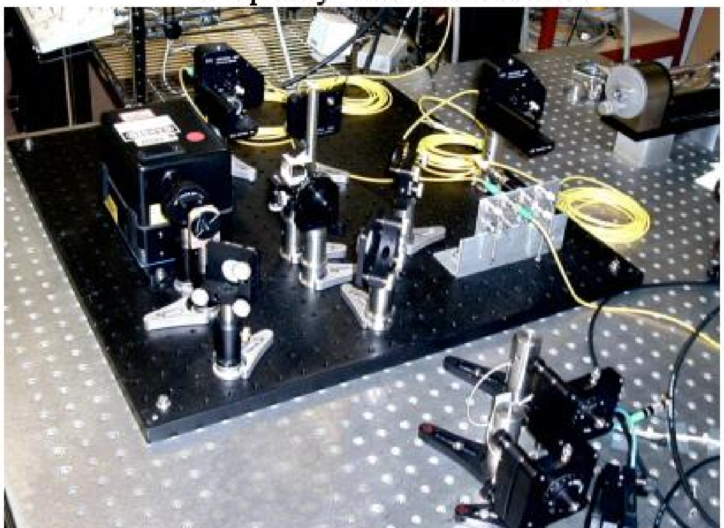
Line centers more sensitive to high-altitudes (Doppler broadening dominates)
Line wings more sensitive to low-altitudes (Pressure broadening dominates)



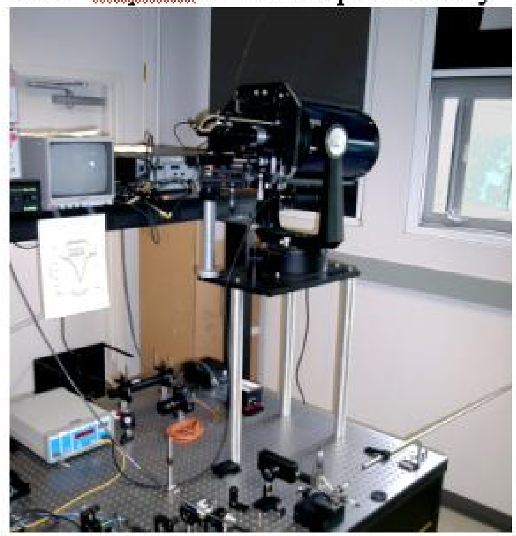


Open Path Atmospheric CO2 Measurement
Test Range (206 m one-way path)

Frequency Tunable diode laser

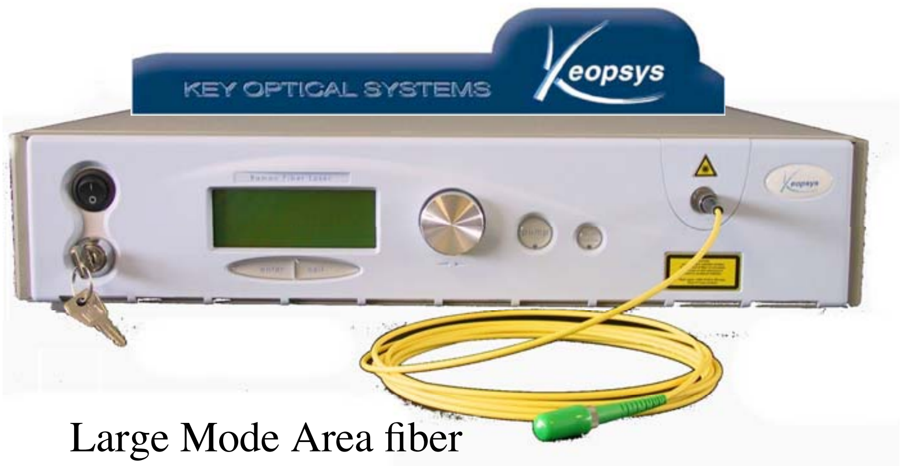


Fiber amplifer & Telescope assembly

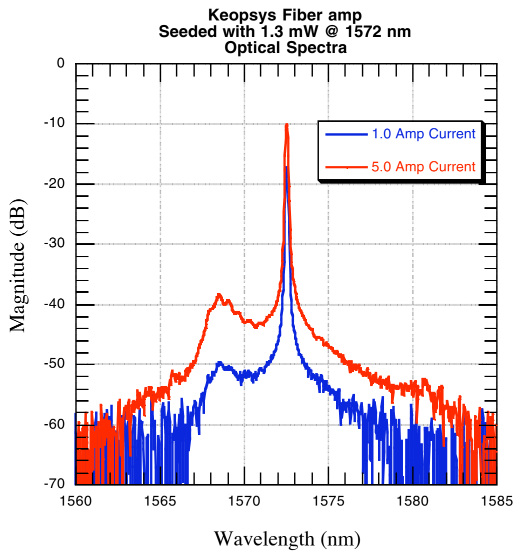


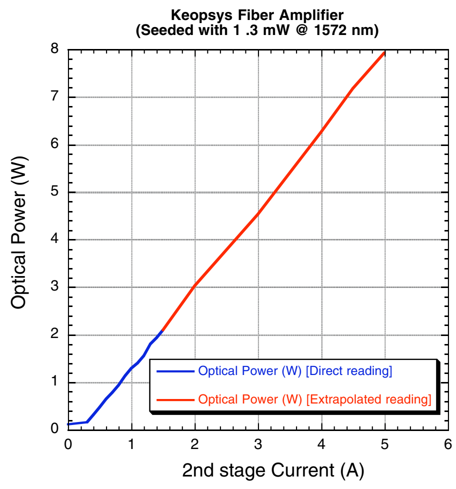
Target (in tree)

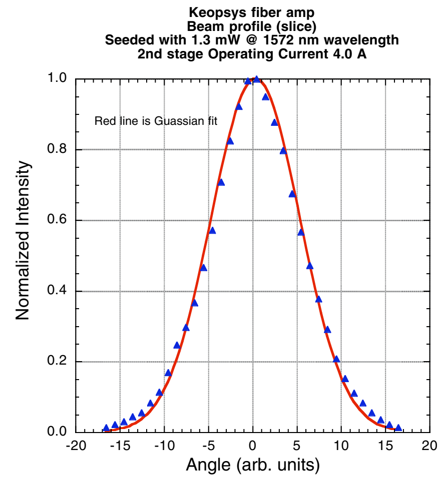
Keopsys 7W custom Er fiber amplifier



Large Mode Area fiber amplifier (Lew Goldberg)

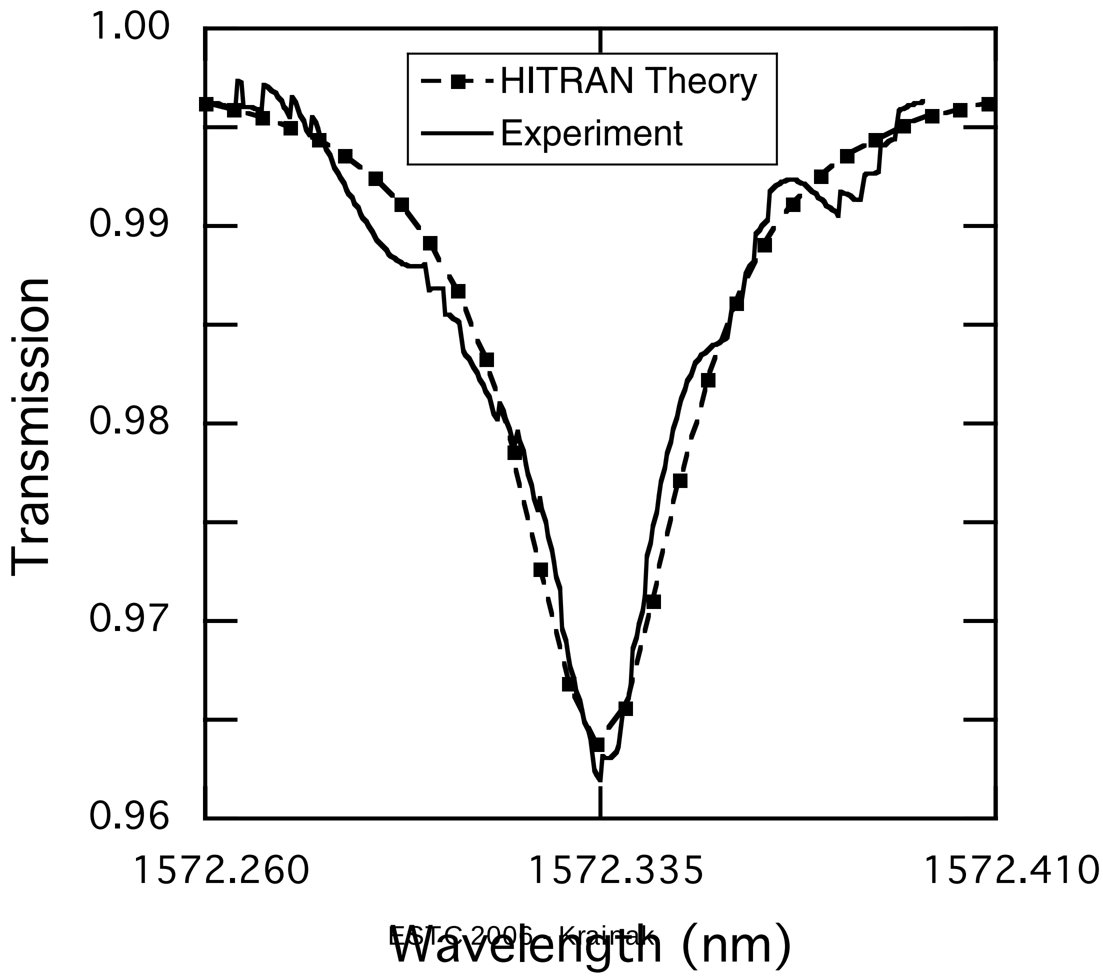




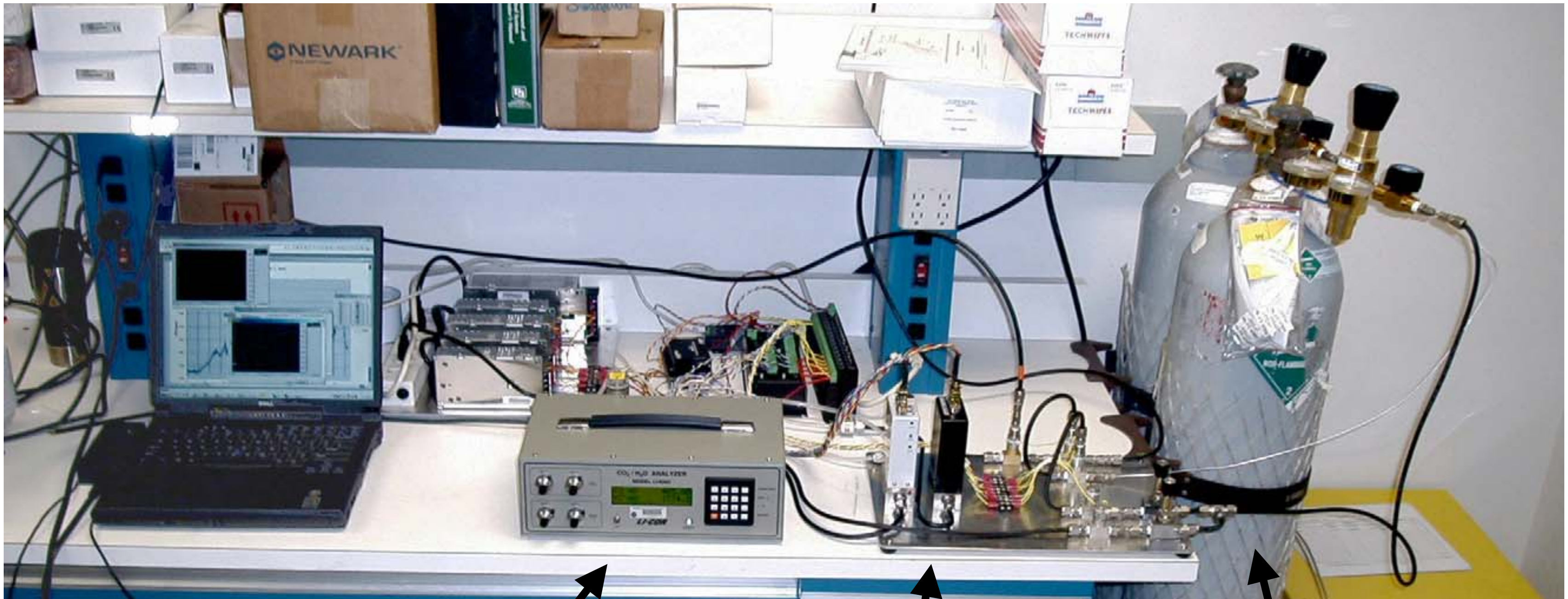


Measurement of atmospheric CO2 with Laser Sounder Prototype Instrument

HITRAN theory and measured (N=2000) atmospheric transmission
at NASA Goddard Greenbelt, MD for 206 m one-way path on 11/21/02 at 4:50 PM EST.
(2000 averages - 200 Hz sweep rate - line scanning technique)
One Parameter (Transmission) Fit



Single point cal/val measurement system
LICOR Measures both H_2O and CO_2

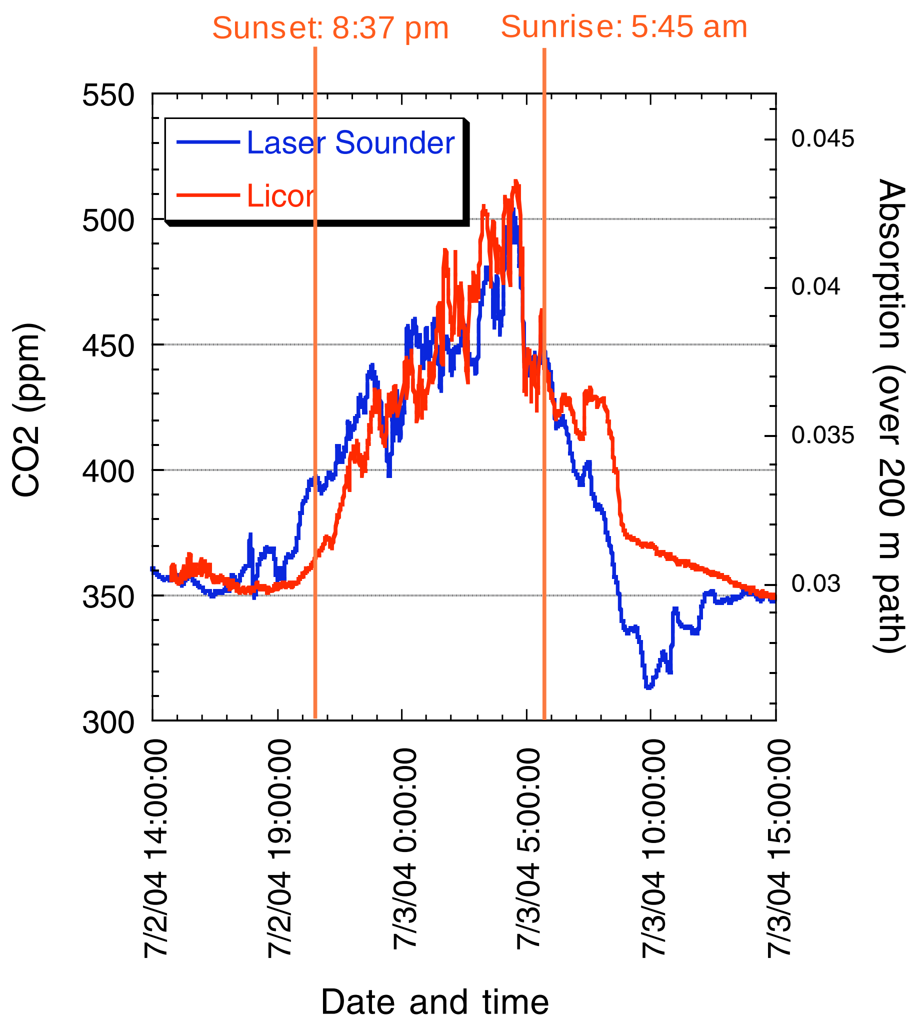


Licor

Reference Gases

Sample/Reference
Gas Selection

Initial open-path measurement of atmospheric CO2 diurnal cycle
Laser Sounder and Licor preliminary comparison



Laser Sounder

200 m one-way open-path

Data offset and scaled

Not yet optimized

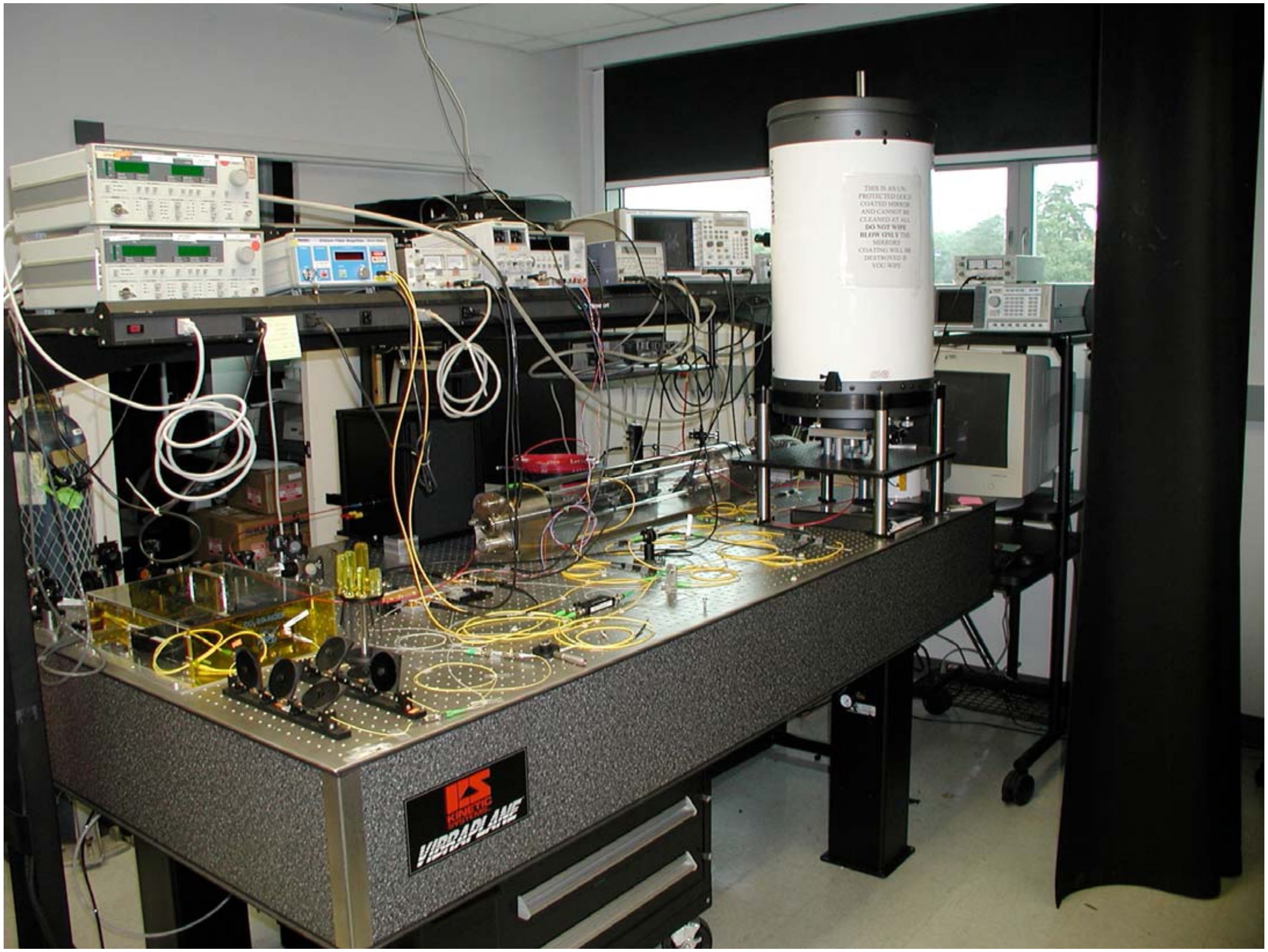
Licor

Industry standard

Single-point location measurement from nearby rooftop

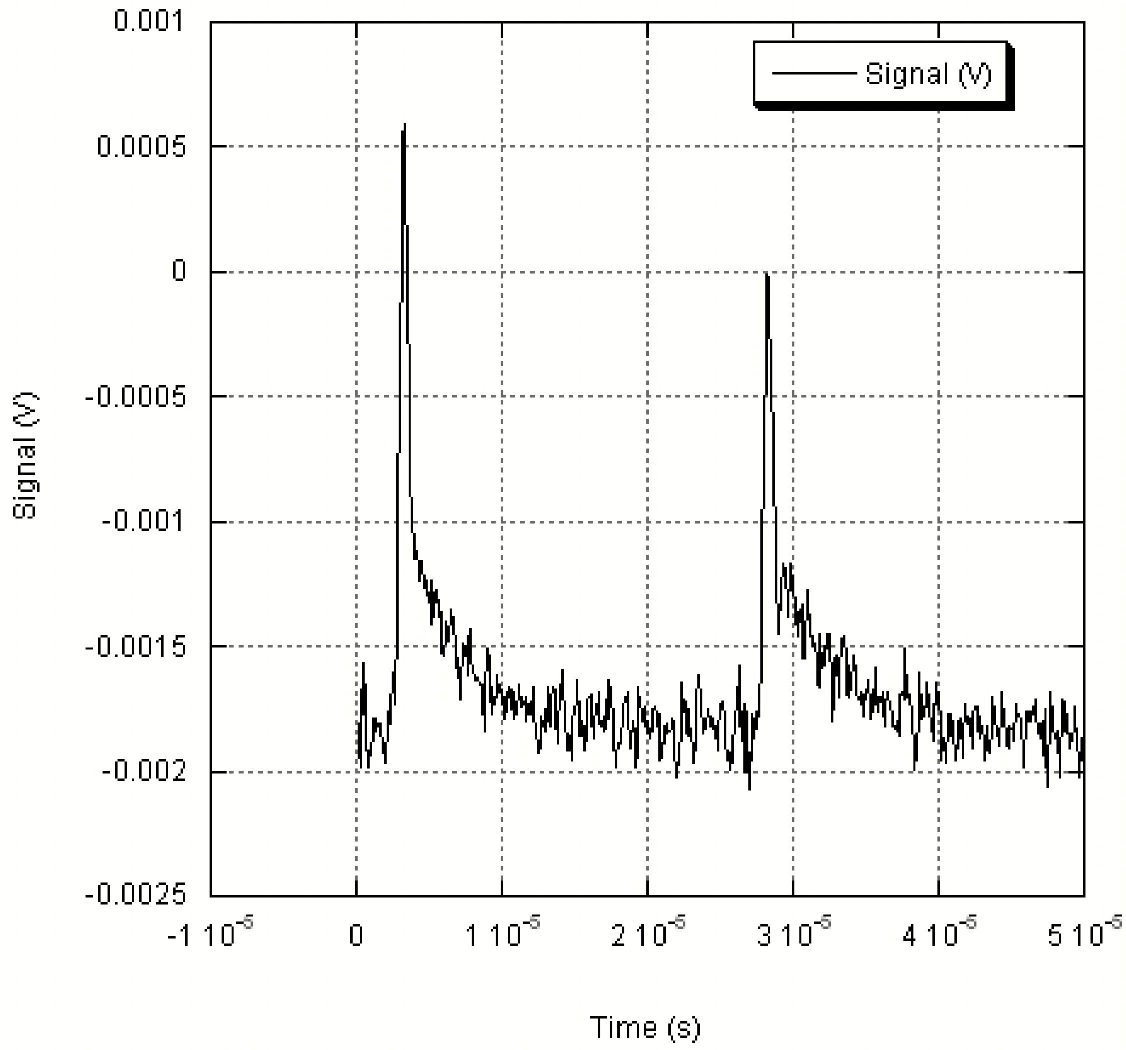
Fiber-laser-based

Differential Absorption Lidar for atmospheric CO2



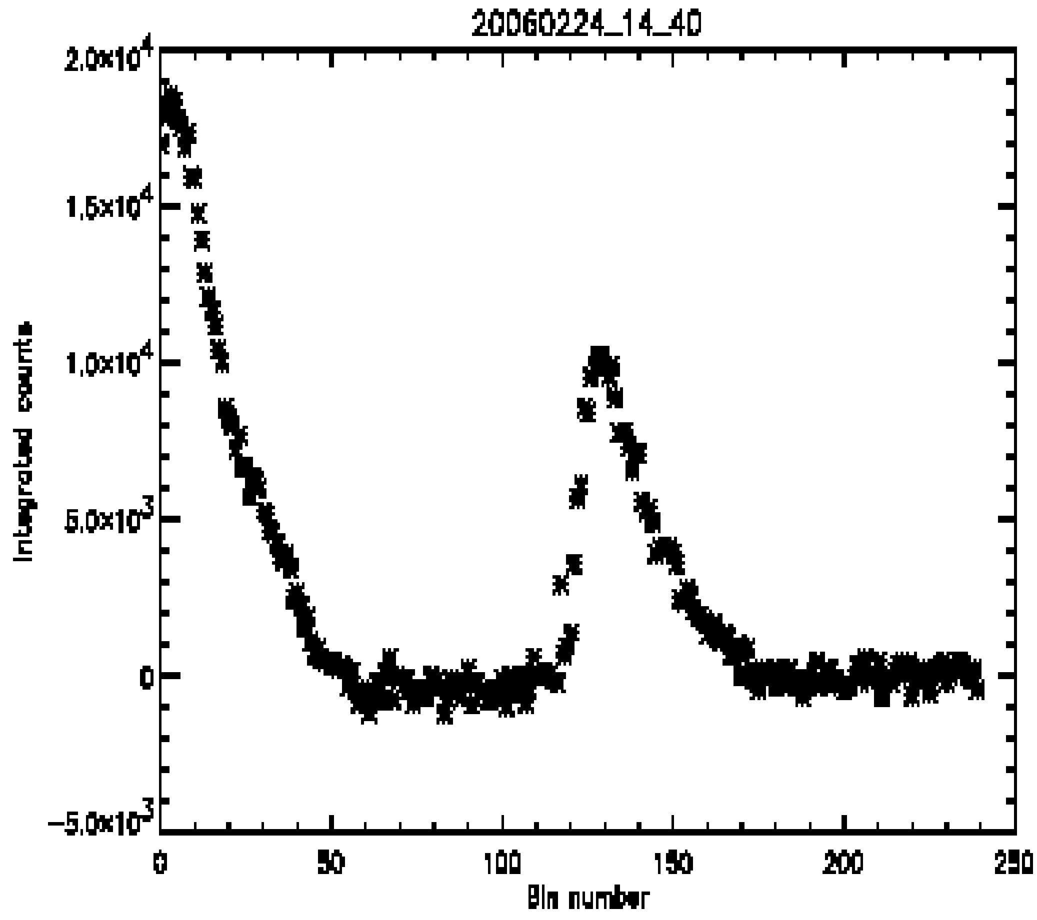
Fiber-laser-based Differential Absorption Lidar

Cloud Echo Signals



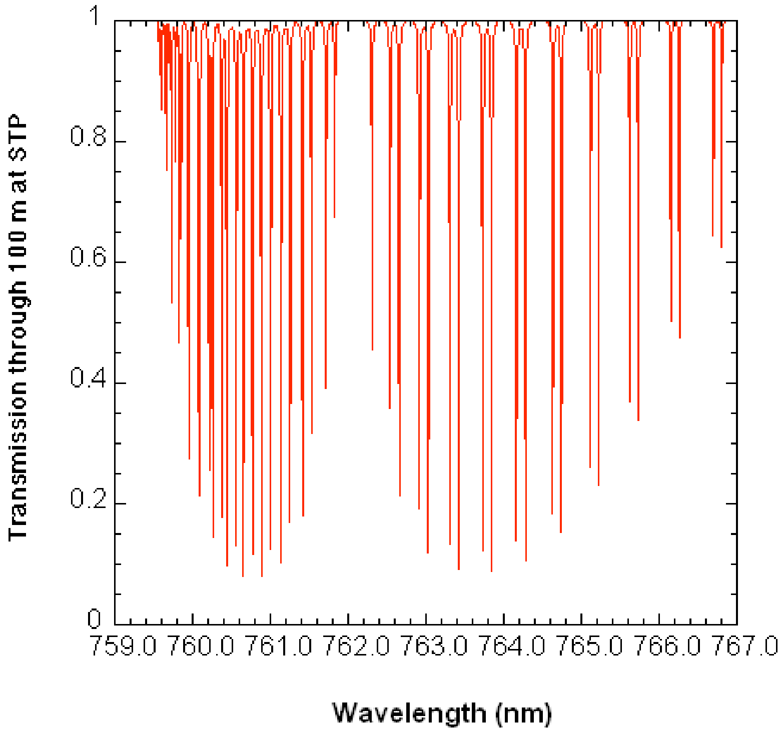
Fiber-laser-based Differential Absorption Lidar

Aerosol and first attempt for CO2 differential absorption returns



Atmospheric Gas Detection/Mapping
OXYGEN =>
TEMPERATURE AND PRESSURE

Oxygen A-Band Spectra

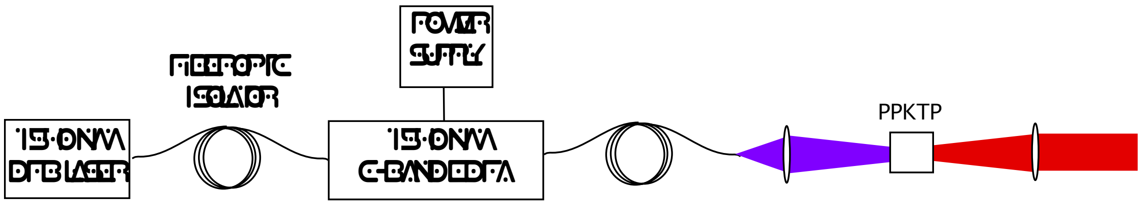


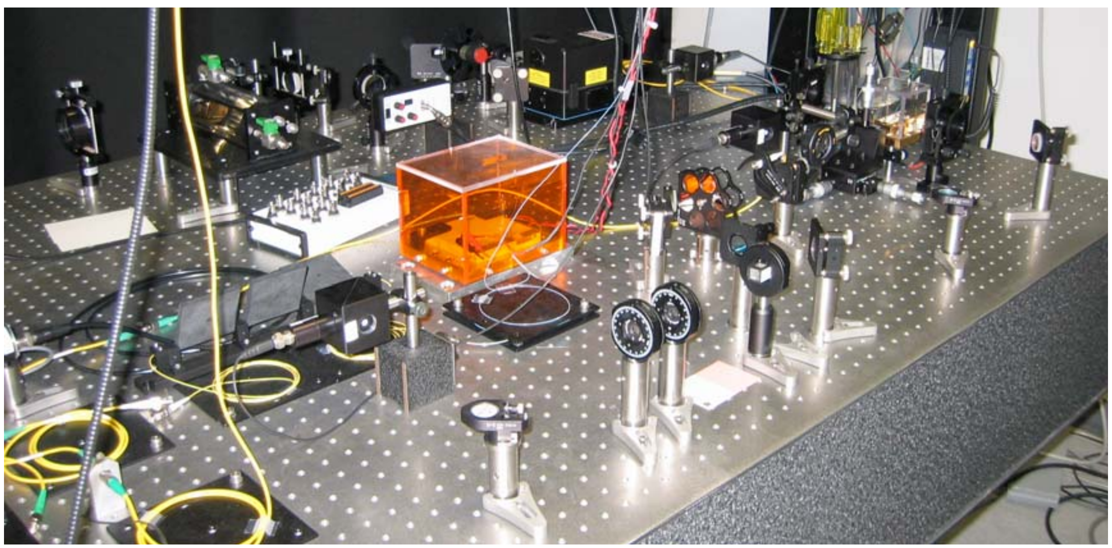
Calculated atmospheric transmission for 100 m path at STP

Advantages of Oxygen A-Band for Pressure Measurement

- Oxygen is well-mixed in atmosphere
- Free of atmospheric contamination
- Others have used this spectral region and measured pressure to ~ 1 mbar and temperature to 1°C accuracy
- Silicon detector efficiency optimized in near IR
- Laser sources available

Oxygen (Pressure/Temperature) Measurement Fiber Laser Transmitter Approach





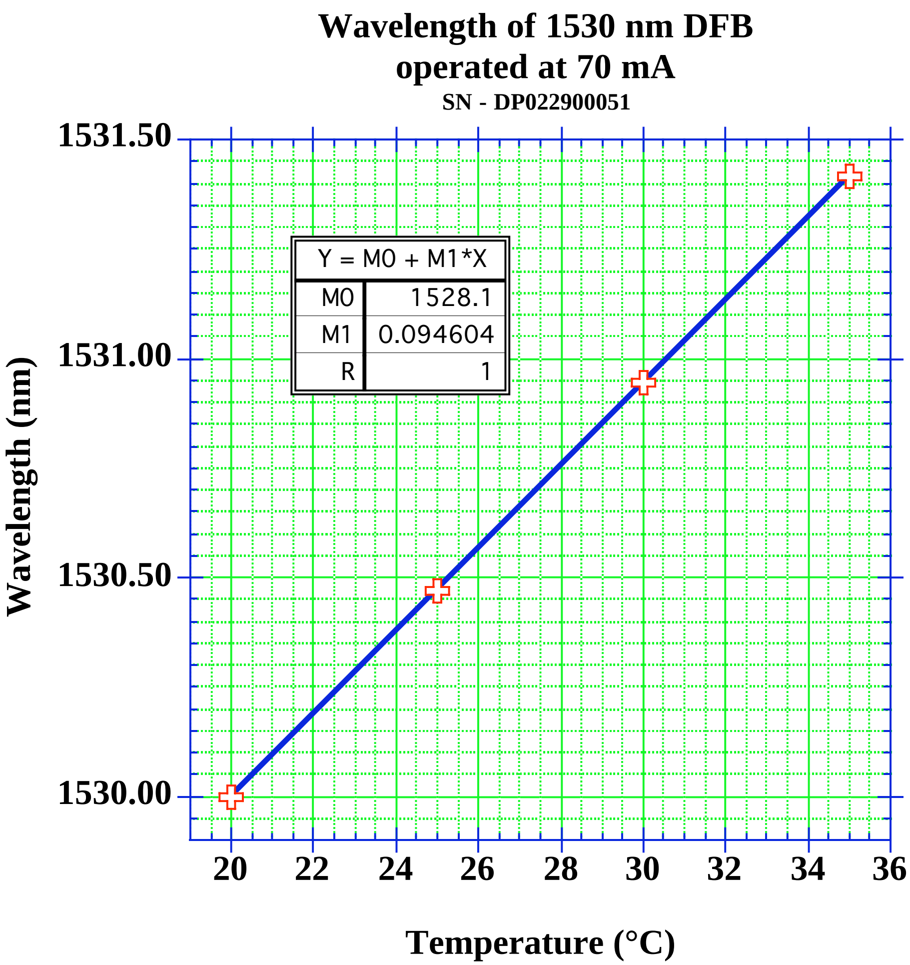
- Distributed Feed Back (DFB) Laser Diode seed laser
  - Narrow band (~1 MHz), tunable, low-power, fiber coupled oscillator
- Erbium-Doped Fiber Amplifier (EDFA)
  - Efficient, single-mode, high-power amplifier
- Periodically-Poled (PP) Potassium Titanium Oxide Phosphate (KTP)
  - Efficient (60%), frequency doubling crystal

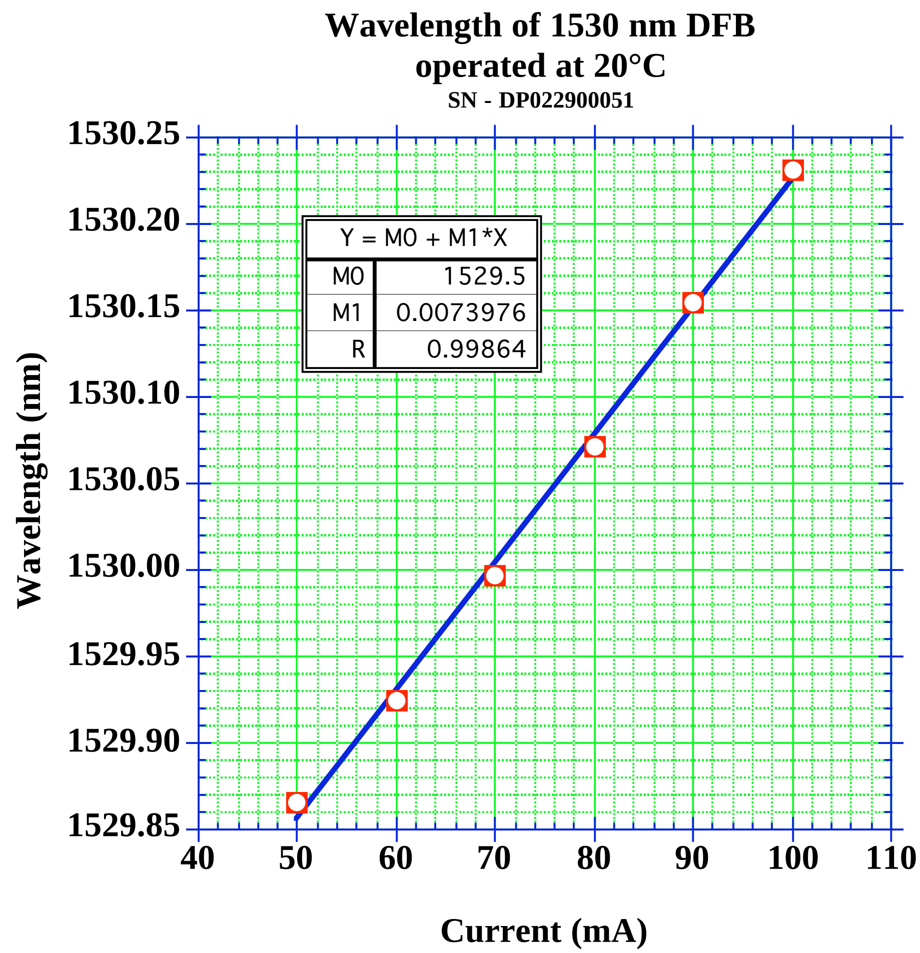
Advantages of transmitter approach

- Tunable, narrow frequency, high-power, single spatial mode, 770 nm, rugged, light-weight, efficient, modular

Fiber Laser Transmitter for O2

Tuning of the fundamental

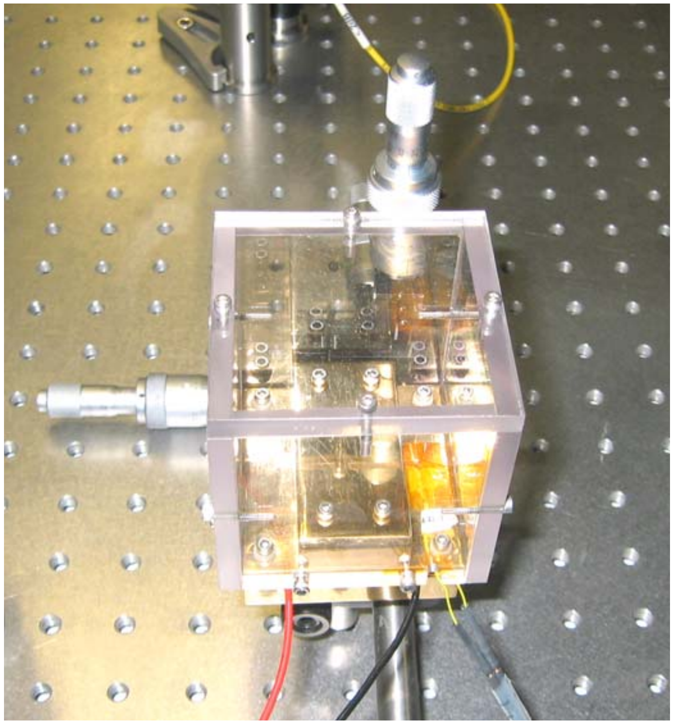


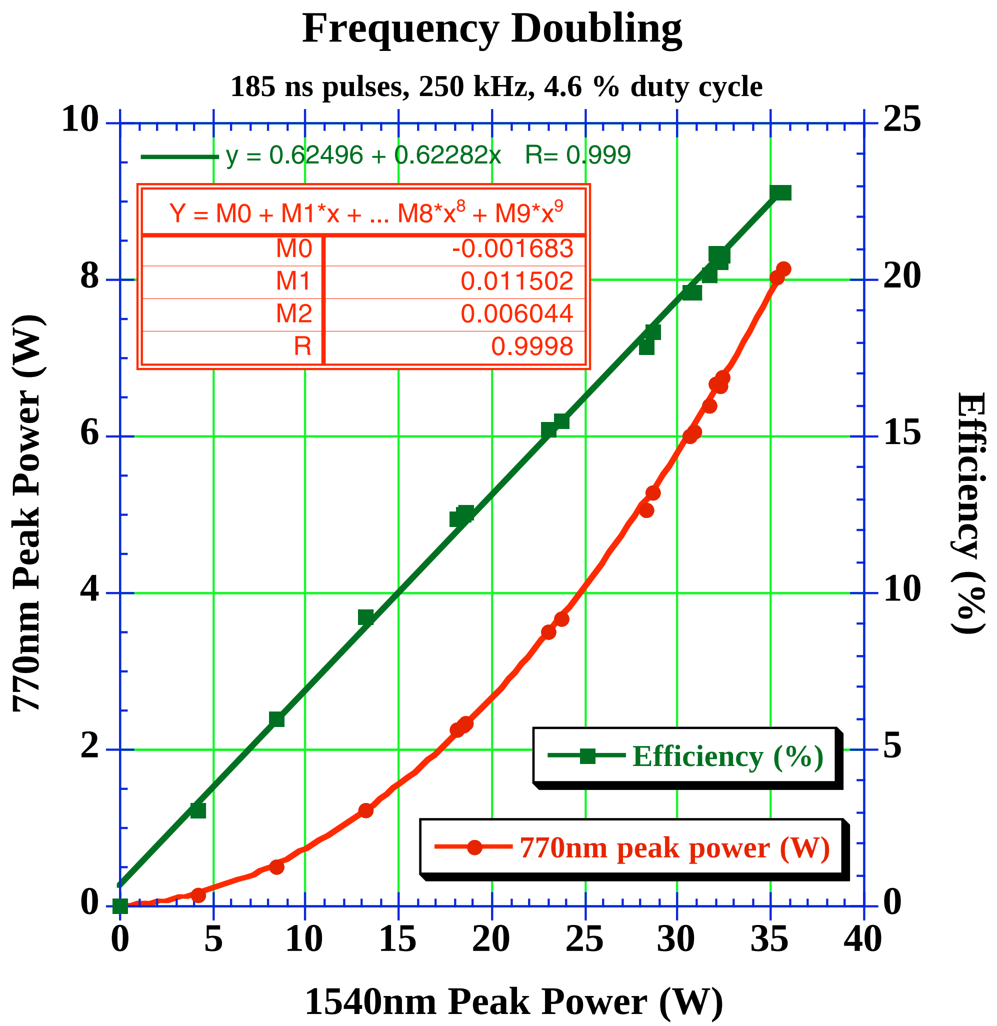


Fiber Laser Transmitter for O2

Frequency Doubling Results

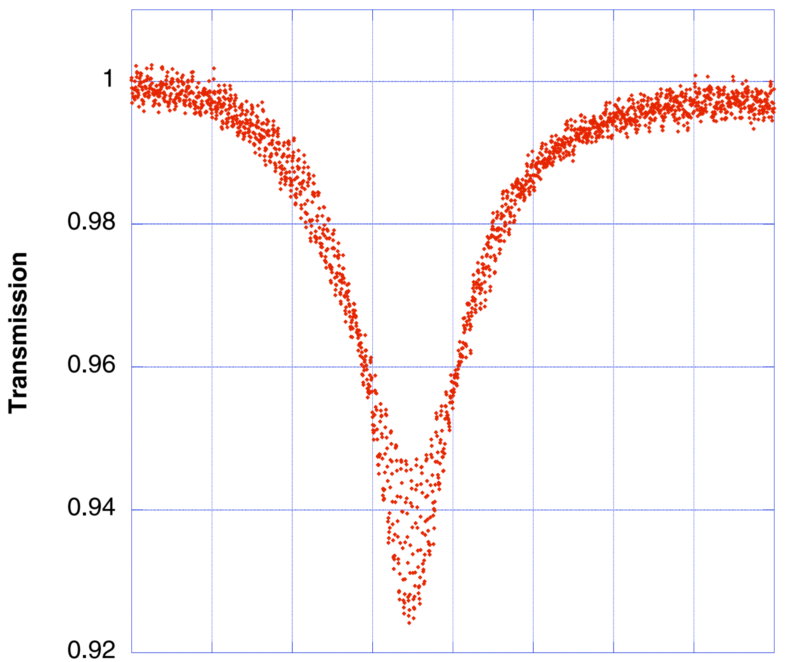
Photo of 30 mm PPKTP crystal in temperature-controlled enclosure





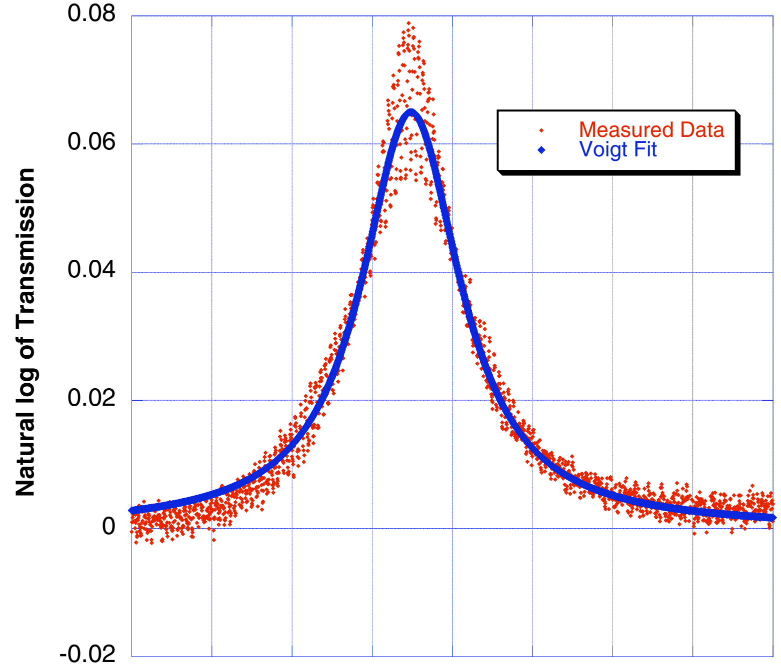
Wavelength Scan of Oxygen Line (With External cavity diode laser) (763.3 nm) in Gas Cell

Transmission of Wavelength-Tuned Laser through gas cell



Wavelength (50 pm/div)

Measurement with Voigt Fit of the Log of Transmission through Gas Cell



Wavelength (50 pm/div)

Atmospheric Gas Detection/Mapping
METHANE and possibly
ALMOST ANY GAS

Laser Sounder Transmitter
for Atmospheric Methane Sensor

110GHz rapid, continuous tuning from an optical parametric oscillator pumped by a fiber-amplified DBR diode laser

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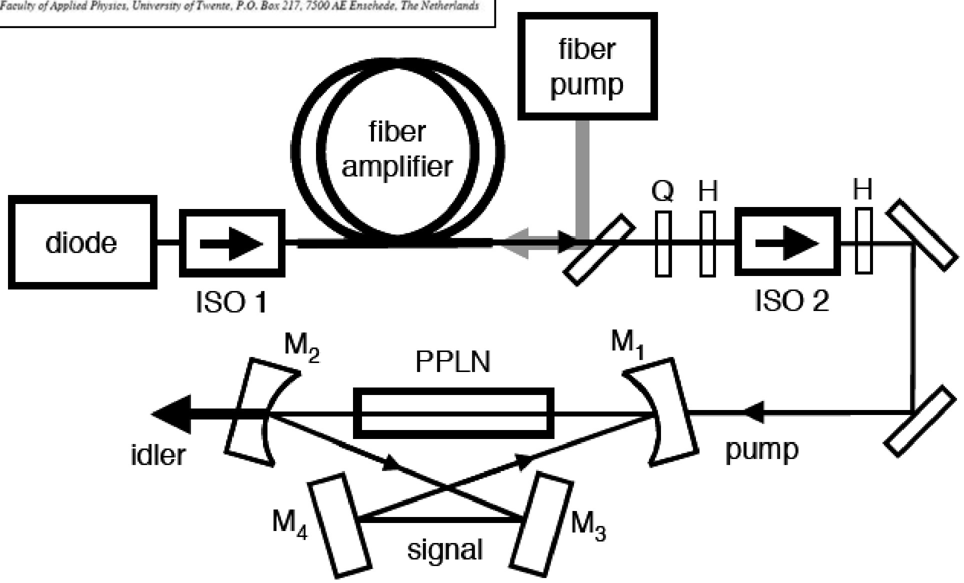


Fig. 1. Schematic of experimental arrangement. diode: 3-section DBR diode laser, fiber pump: 25W fiber-coupled 976nm diode bar, ISO 1: 60dB optical isolator, ISO 2: 30dB optical isolator, Q: quarter wave plate, H: half wave plates, M_1-M_4: OPO cavity mirrors, PPLN: 40mm PPLN crystal in oven.

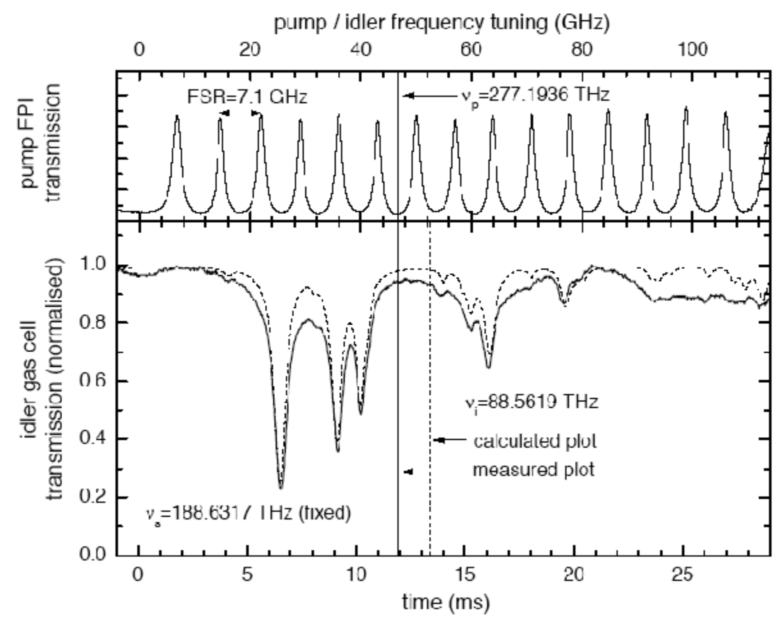
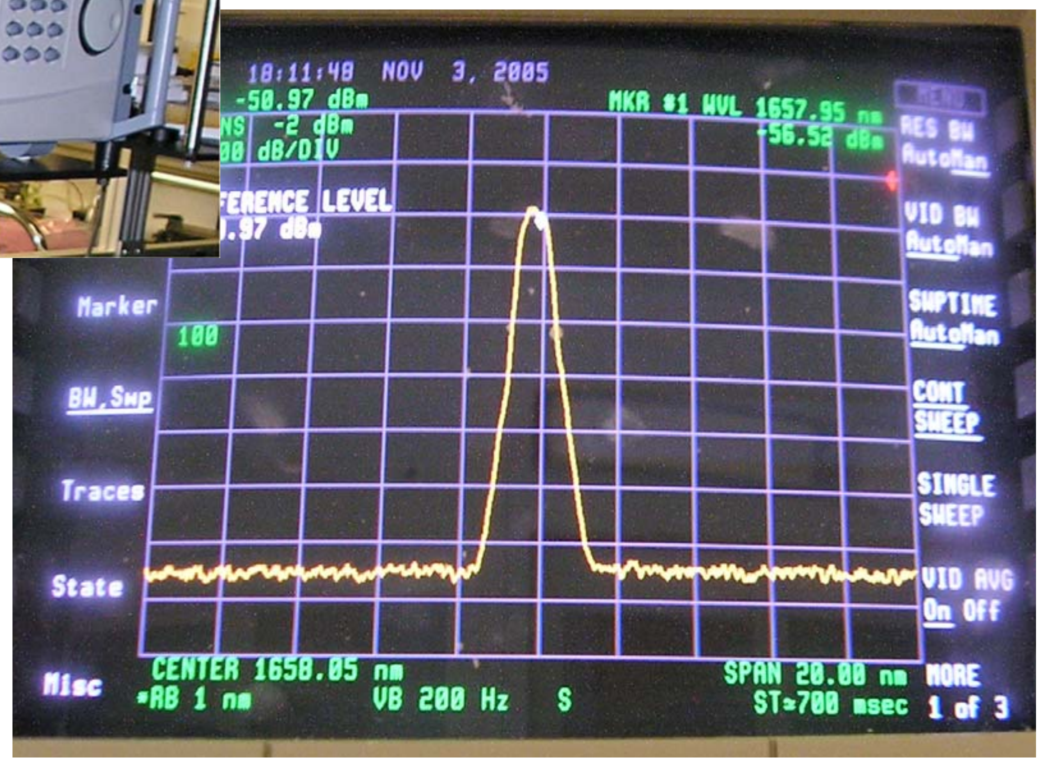


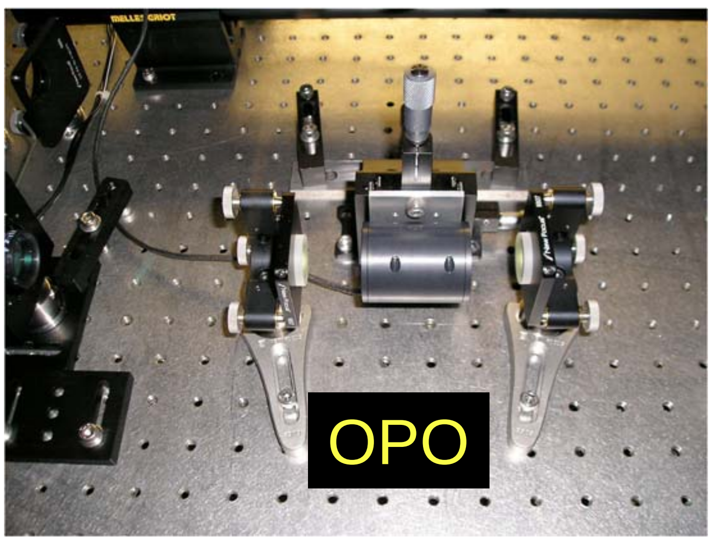
Fig. 3. Upper trace: Rapid, mode-hop free tuning of the seed laser over 110 GHz observed in the transmission of a Fabry-Perot interferometer with 7.1GHz FSR. Lower trace: corresponding OPO idler tuning observed in the transmission through a 90 cm cell containing 15 mbar CH_4 buffered to 0.52 bar in air (solid line), calculated cell transmission derived from HITRAN data (dashed line). Pump tuning axis was calibrated from the Fabry-Perot transmission and an absolute frequency reference, measured under static conditions, is indicated. A corresponding idler frequency reference is indicated for the measured and calculated plots. The signal frequency remained constant throughout the measurement. The total time scale represents one half of a single period of the 17 Hz tuning function.

21 February 2005 / Vol. 13, No. 4 / OPTICS EXPRESS 1234

High-power tunable laser for methane spectroscopy

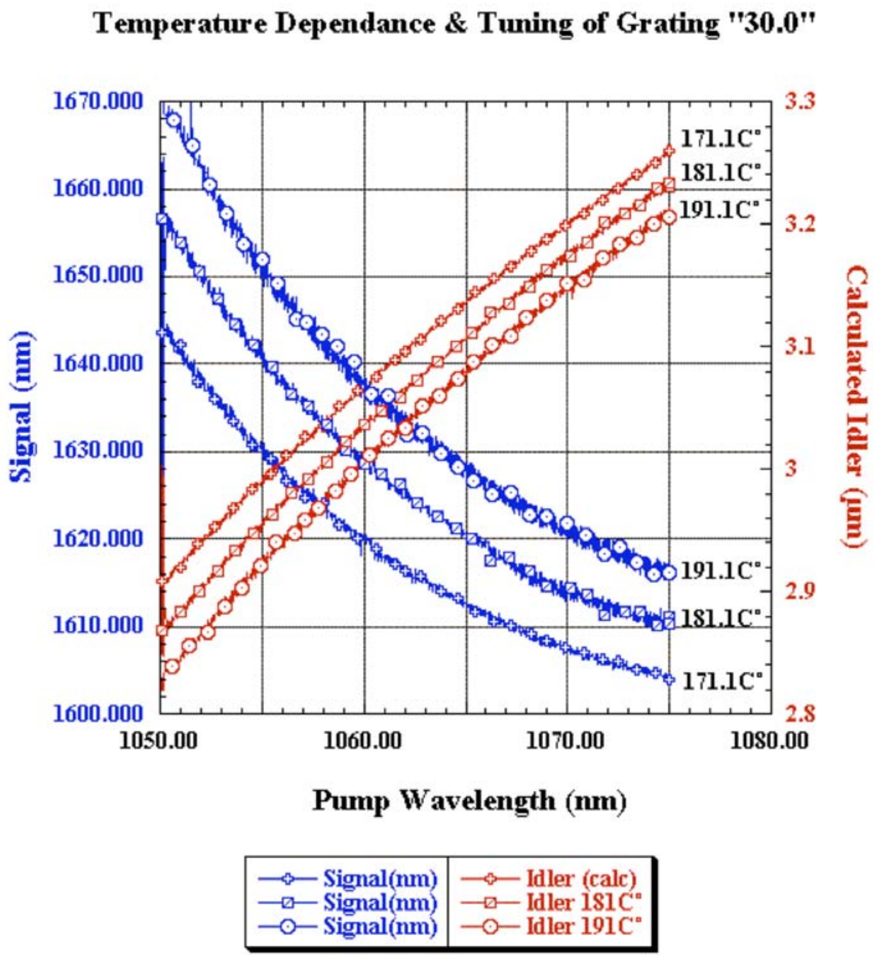
Yb fiber transmitter pumping an Optical Parametric Oscillator (OPO)





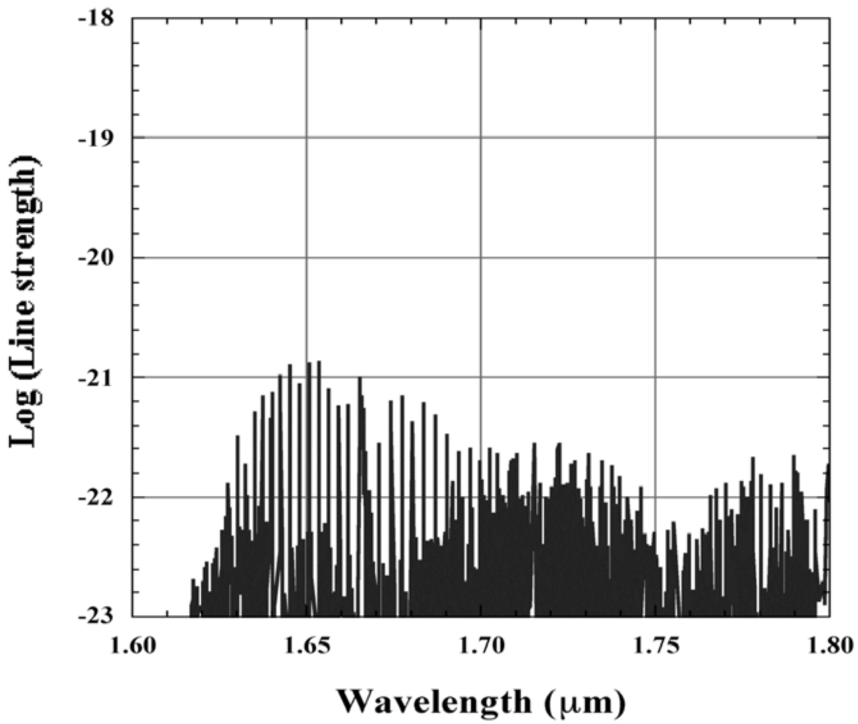
High-power tunable laser for methane spectroscopy

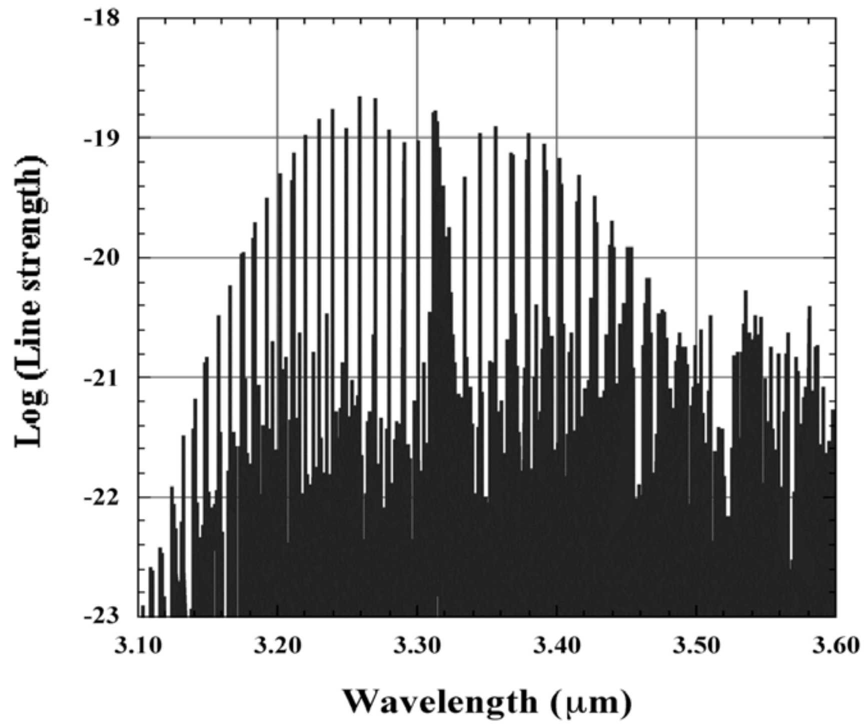
OPO output wavelengths



Measured OPO signal output wavelength (left-side ordinate) as a function of master oscillator wavelength for the 30.0 micron periodically-poled lithium-niobate crystal grating spacing at three different crystal temperatures. Right-side ordinate shows calculated idler OPO output wavelength as a function of master oscillator wavelength. This can be achieved by using mirrors with the proper transmission and coatings in the mid-infrared (i.e. near 3 microns).

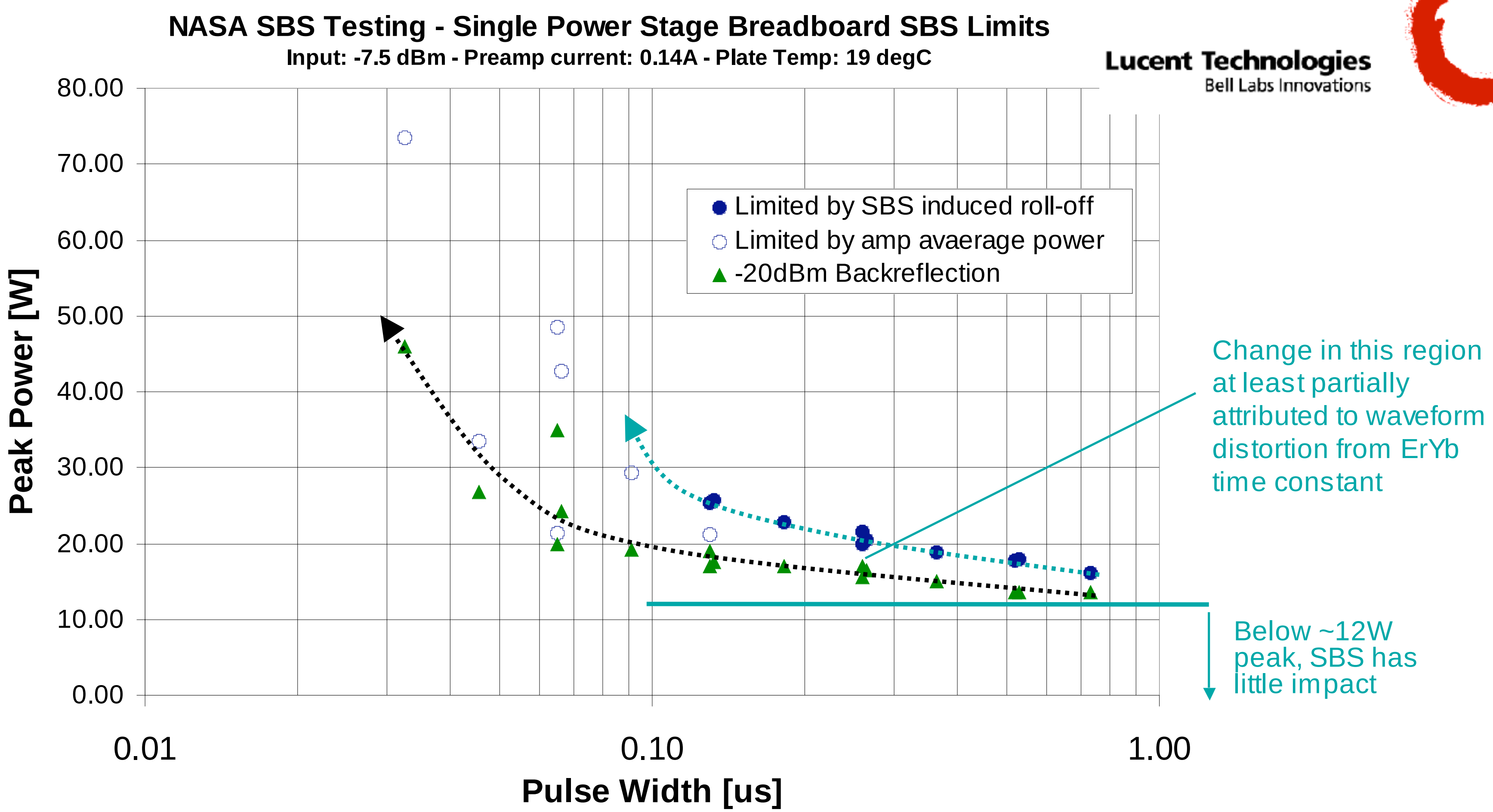
Comparison of methane absorption line strengths near 1.65 and 3.25 micron wavelengths.





Narrow Linewidth/Single-Frequency Fiber Laser/Amplifier Limitations Stimulated Brillouin Scattering (SBS)

Er Fiber Amplifier (2W)
SBS Limits



SBS mitigation with new fiber designs

CLEO 2006

CThAA1.pdf

Engineered refractive index profiles for high power fiber lasers

Donnell Walton, Stuart Gray, Ji Wang, Ming-Jun Li, Xin Chen, A. Boh Ruffin, and Luis Zenteno
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Abstract: We demonstrate engineered refractive index profiles for the mitigation of nonlinear optical impairments such as stimulated Raman scattering and stimulated Brillouin scattering. These fibers offer performance improvements over conventionally used large mode area fibers.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3280) Laser amplifiers; (190.5890) Scattering, stimulated

Fiber lasers and amplifiers
SUMMARY (1)

- NASA's weight, power, reliability, and cost requirements for future space-based laser instruments demand new approaches

- Fiber lasers and amplifiers offer numerous advantages and opportunities, particularly with new instrument architectures

- Near-term opportunities include laser communications, high-resolution ranging/mapping and atmospheric gas measurement/profiling/mapping.

- Yb fiber MOPA pumped OPO coupled with HgCdTe integrating detector and sounder architecture offers great promise for a "universal" gas detection/profiling/mapping instrument.

Fiber lasers and amplifiers
SUMMARY (2)

- Two airborne instrument demonstration recently awarded (3 year program culminating in airplane demonstration):

  1. Laser Sounder for Atmospheric CO2 Measurements from Orbit - Technology Improvements, Ground and Airborne Demonstrations, and Space Instrument Definition [Single-frequency (1571 nm), 10 W ave, 100 W peak]

  2. Push-Broom Laser Altimeter Demonstration for Space-Based Cryospheric Topographic and Surface Property Mapping [1 μm wavelength, 1- 10 kW peak]

- We look forward to further advances particularly in narrow linewidth high-peak power devices and techniques to overcome limitations (e.g. SBS)